



Comprehensive Analysis Of Regenerative Braking System In EV

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TATA TECHNOLOGIES

1. Abstract

In recent years, various power generation techniques have gained prominence, and automated vehicles are anticipated to have a significant future. Road transportation remains the primary mode of travel, and the use of cars has surged, leading to increased demand for petrol and diesel. This has spurred the development of electric vehicles (EVs), with government support encouraging innovation in this sector. In public parking facilities, only EVs parked in dedicated spaces with charging points can access charging services. However, installing a charging point at every parking slot is prohibitively expensive.

This project proposes a novel solution: implementing a Wireless Charging Path (WCP) on Electric Vehicle Service Roads (EVSR) within public transport facilities. This would allow EVs to charge wirelessly while driving on designated paths. The wireless charging system eliminates the need for cables, reduces charging wait times, and integrates a solar energy-based generation system. Additionally, the system incorporates artificial intelligence to optimize its operation.

Keywords: Automated Vehicles, Regenerative Charging, Electric Vehicles, Artificial Intelligence, Machine Learning.

2. Introduction & Brief Description

Relying solely on limited petroleum resources jeopardizes the vision of widespread car ownership. As such, developing regenerative braking systems for electric vehicles (EVs) is a crucial strategy for addressing this challenge. In traditional vehicles, kinetic energy is lost as heat when brake pads rub against wheels during braking, with this heat dissipated into the air, resulting in significant energy waste. The amount of energy lost varies depending on the frequency, intensity, and duration of braking. Regenerative braking offers a solution by temporarily storing some of the vehicle's kinetic energy during deceleration. Instead of being wasted as heat, this energy is redirected by a power transfer system to an energy reserve. This conserved energy can then be used for subsequent vehicle acceleration or other electrical purposes. Given the frequent braking involved in driving, especially in buses, taxis, delivery vans, and similar vehicles, regenerative braking presents a substantial opportunity for energy conservation and efficiency.

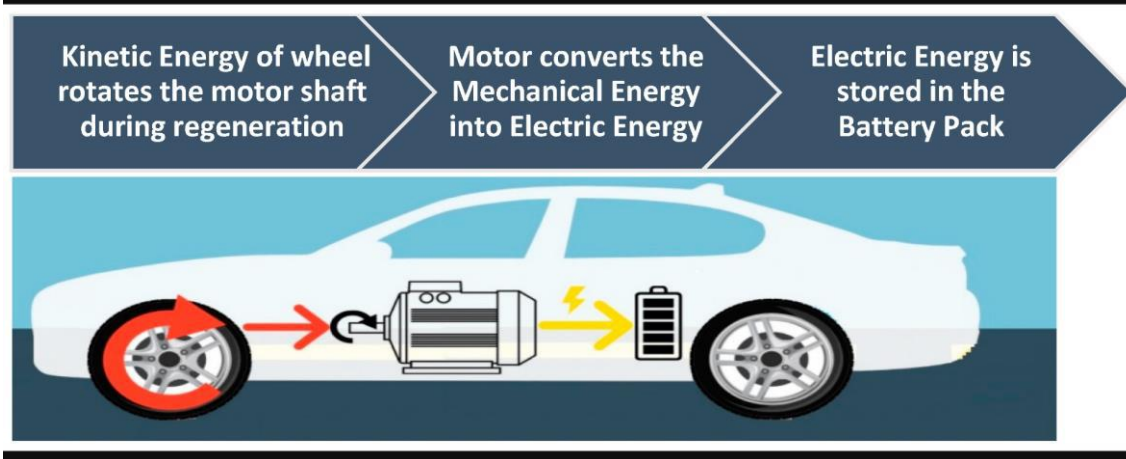


Figure 1: Conceptual diagram of regenerative braking.

2.1. Regenerative Braking

2.1.1. Different Regenerative Braking Strategies

A regenerative braking system (RBS) designed for parallel hybrid electric vehicles (PHEVs) that recovers energy based on vehicle characteristics. They calculated the maximum front and rear brake forces by considering slopes and intercepts. The RBS algorithm was initially modeled using an analogue MATRIXx algorithm and then discretized by developing the code with MATRIXxAutocode. The process began by establishing a relationship between hydraulic brake pressure and the electric brake torque generated by regenerative braking. The magnitude of regenerative braking torque was subsequently calculated as a function of motor speed relative to torque. During braking, the engine is disengaged from the drive wheels to minimize frictional losses, and regenerative braking is achieved using a high-efficiency, single-gear, direct-drive transaxle. By removing regenerative brake torque from the engine-driven wheels, both energy recovery and braking performance are enhanced. A similar simulation study on hybrid electric vehicles (HEVs) compared the results of baseline systems (without RBS) and the proposed regenerative braking strategies in terms of system behavior, fuel economy, and emissions. The findings indicated improved performance, efficiency, and reliability at a reduced cost.

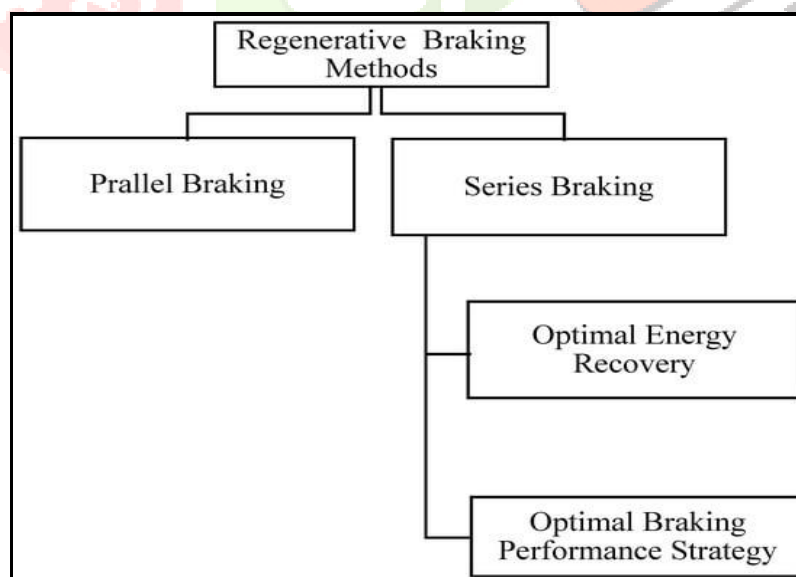


Figure 2: Shows a layout that represents the methods of regeneration of braking

Figures 3 and 4 illustrate the graphical representations of series and parallel regenerative braking, showing the relationship between braking forces and pedal pressure. When the wheel speed exceeds a certain threshold and the desired vehicle deceleration is either below or above the required level, either full electric regenerative braking or a combination of mechanical and regenerative braking is applied, respectively. Additionally, a new optimal braking performance strategy, introduced in 2007, dictates that

when the required total braking force is less than or exceeds the electric motor's capacity, total regenerative braking or combined electric and mechanical braking is utilized accordingly. The total mechanical braking follows a specified I-curve as depicted in the graph, potentially leading to a 12% reduction in fuel consumption for hybrid electric vehicle (HEV) powertrains.

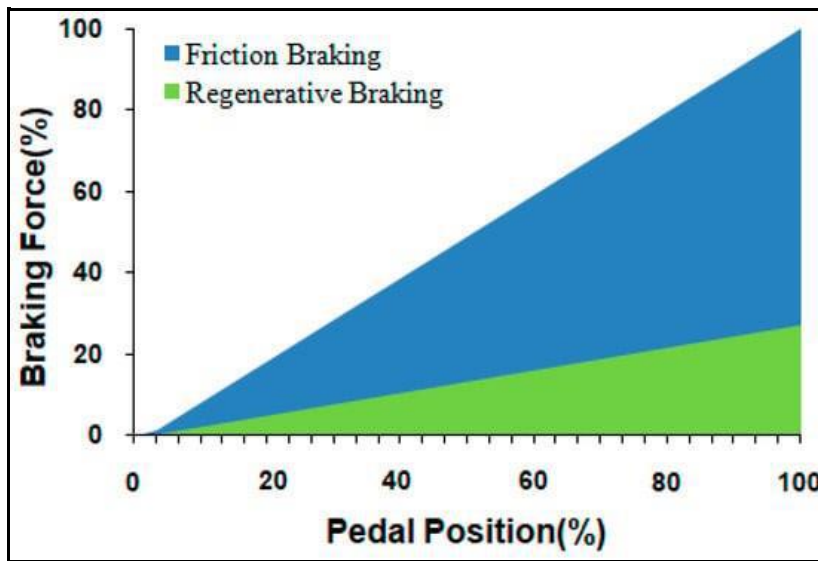


Figure 3: Parallel regeneration braking

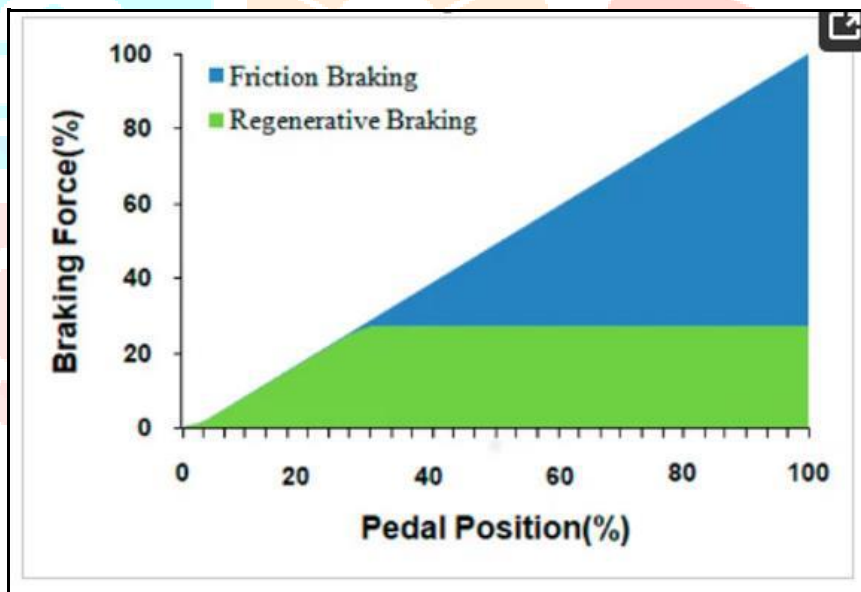


Figure 4: Series regeneration braking

2.1.2. Combined Regenerative Braking and Fuzzy Logics System

A Proportional–Integral–Derivative (PID) controller is commonly used for controlling a brushless direct-current (BLDC) motor, while a fuzzy logic controller is employed to distribute braking force, making the regenerative braking system (RBS) adaptive to the BLDC motor. This approach simplifies the control of both braking force distribution and the BLDC motor. In this system, the state of charge (SOC) and braking force are input variables for the fuzzy controller, and their effectiveness is simulated using Simulink. The simulated performance of the RBS closely matches practical results, indicating that the system successfully optimizes regenerative braking and extends driving distance. However, in terms of steady-state tracking error and response speed, experimental results show that an H_∞ robust controller, driven by a permanent

DC motor, outperforms a standard PID controller. The H_∞ controller can be further optimized by integrating the sliding phase and hitting phase, which enhances the parameters of a sliding mode controller. The system's gain matrix ensures robust stability and disturbance rejection.

The regenerative braking controller integrates a backpropagation neural network (BPNN), a radial basis function neural network (RBFNN), and a sliding mode controller (SMC or NNSMC). The BPNN adapts the switching gain of the SMC online to prevent oscillations, while the RBFNN identifies and predicts system parameters. Experimental results indicate that NNSMC outperforms standard SMC in terms of response speed, steady-state tracking error, and resistance to regenerative braking disturbances. This approach also increases energy recovery, extends battery life, and enhances driving range by approximately 6%. An NN-based PID controller can further increase driving range by 5.3%. Additionally, a neural network-based switching reluctance motor (SRM) drive control technique has been developed to meet regenerative braking requirements. However, iron loss at high rotor speeds leads to lower energy recovery efficiency at reduced braking torque.

2.1.3. Other Regenerative Braking System Strategies

There are three distinct approaches to regenerative braking in electric vehicles (EVs): the maximum regeneration efficiency approach, the good-pedal-feel strategy, and the coordination strategy. MATLAB/Simulink models of an EV's regenerative and frictional blending brakes were developed to analyze the control effects and regeneration efficiency of these strategies during a typical deceleration process. The results from both practical applications and simulations indicate that the maximum regeneration efficiency method offers a balance between brake comfort and safety. However, the good-pedal-feel approach and the coordination strategy outperform the maximum regeneration efficiency strategy in terms of both brake comfort and regeneration efficiency. For the ECE driving cycle, the implementation of this regenerative braking technology improved fuel economy by over 25%. Additionally, the study proposed incorporating an electronically controlled brake subsystem that independently distributes braking forces to all four wheels in hybrid electric vehicle (HEV) electro-mechanical brake (EMB) systems. The internal combustion (IC) engine, electric motor, battery, and transmission were all modeled as part of the HEV powertrain to simulate the performance of the regenerative braking system (RBS) in MATLAB/Simulink. The control performance of the EMB system was evaluated by simulating the HEV's regenerative braking under various driving conditions. The studies also examined the HEV with an automated manual transmission (AMT), analyzing the methodology of AMT downshifting and the characteristics of regenerative braking at different gear positions and downshifting strategies. Based on this analysis, two downshifting strategies were developed using rule-based and dynamic programming (DP) algorithms. Hardware-in-the-loop (HIL) studies showed that integrating downshifting strategies with regenerative braking can increase energy conservation by 10.5% to 23.2% compared to systems without downshifting. Further HIL testing compared a "modified control strategy," which focused on maximum regenerative efficiency, with a "baseline control strategy."

3. Conclusion

Various regenerative braking techniques have been introduced to optimize energy extraction during braking. Two primary techniques are commonly implemented: the parallel hybrid braking system and the fully controllable hybrid braking system. The fully controllable hybrid braking system further incorporates sub-strategies such as optimal braking performance and optimal braking energy recovery, both of which are based on the vehicle's braking distribution. Numerous studies have compared these strategies, highlighting their respective advantages and disadvantages. In electric vehicles (EVs) and hybrid vehicles, conventional regenerative braking is often integrated with Anti-lock Braking Systems (ABS) to enhance overall braking efficiency. Additionally, downsizing the automated manual transmission (AMT) has led to higher regenerative braking efficiency, as lower brake torque typically results in greater energy loss. However, high rotor speeds can cause iron

losses, reducing the energy recovery efficiency during regenerative braking. To address these challenges, a combined H_∞ controller has been implemented in regenerative braking systems (RBSs), utilizing fuzzy logic to optimize performance while accounting for the state of charge (SOC) of the battery. The H_∞ controller is further enhanced by integrating it with Proportional-Integral-Derivative (PID) and sliding mode controllers (SMC) to improve the overall braking process.

