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Braking Systems of Electric Vehicles

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A B S T R A C T

The global focus on addressing issues such as global warming, fossil fuel scarcity, and passenger vehicle safety has led to a surge in interest and investment in the research and development of electric vehicles (EVs). Significant strides have been achieved in recent years in the enhancement of system structures and the development of key components for electric vehicles. Despite these advancements, there remains a performance disparity between electric vehicles and traditional counterparts in terms of driving range, energy efficiency, powertrain effectiveness, and safety. This term paper gives a thorough overview of electric vehicle braking systems, emphasizing its unique qualities and benefits. The braking system is a critical component in ensuring the safety and performance of modern vehicles. As automotive technology advances, there is a growing need for braking systems that not only provide efficient deceleration but also address challenges posed by diverse driving conditions. This abstract discusses developments and innovations in braking systems aimed at enhancing safety, performance, and overall driving experience. Some of the those braking systems are regenerative braking, brake by wire system.

Keywords: Electric braking, Regenerative braking , brake by wire system , energy recovery.

1. Introduction

1.1 What is Electric Braking?

A "Pure Electric Braking System" has the capability to bring a vehicle to a complete standstill without relying on friction braking. This is achieved solely through the utilization of electric brakes. These electric brakes operate through regenerative braking, converting kinetic energy into electrical energy as the vehicle slows down. By employing this system, the vehicle can come to a standstill without the need for traditional friction brakes, enhancing efficiency and reducing wear on friction brake components.[1] The electric brake means regenerative brake is activate when the motor operates as generator.[2] In the process of regenerative braking, the kinetic energy present at the wheel is transformed into electrical energy. The amount of regenerated energy is contingent upon various factors, including the speed of the vehicle, its inertia, and the prevailing road and traffic conditions.[3]

1.2 Need of Electric Braking

Recently electric brake system is noticed in electric vehicles as essential because of its nice speed controllability, environment friendly, energy saving, good maintainability. A frequently employed electric railway system relies heavily on a mechanical friction brake system during extended periods. This system extensively employs friction to bring railroad cars to a halt, utilizing compressed air as a compressor for the brake mechanism. The application of compressed air intensifies the force applied to the vehicle's disk brake, creating an aggressive braking effect. Known as the air brake, this approach has gained widespread acceptance due to its high level of reliability. However, over time, it has revealed certain enduring issues associated with its prolonged use [2].The following reasons causes the need of electric braking system ,they are :

1. Slow responsive

The generation of a brake command signal initiates the production of air pressure, which in turn activates the braking force. This air pressure causes the brake shoes to adhere to the disks or wheels, a process that typically takes several hundred milliseconds.[2]

2. High Maintaining Cost

It's an inevitable occurrence that both the brake disks and shoes undergo wear and tear. This wear is primarily a result of the friction generated between the brake disks and shoes, leading to increased maintenance costs for the vehicle.[2] 3.Environment Deterioration

The abrasion of the brake system produces particles that contribute to environmental degradation and noise. Additionally, the heat generated during braking from the disks and brake shoes negatively impacts the environment..[2]

1.3 Superiority of electric vehicles over mechanical brakes

In contrast to the drawbacks associated with mechanical braking discussed earlier, utilizing a motor in the braking system offers several advantages. This includes rapid responsiveness and precise control due to the generation of specific braking power. There is minimal wear and tear, primarily occurring between the rail and wheel. Moreover, this approach is environmentally favorable as it involves the regeneration of kinetic energy into electric energy. [2]In our contemporary world, the escalating costs, limited fossil fuel resources, and growing environmental concerns have prompted the widespread adoption of a clean and sustainable mode of transportation—electric vehicles (EV). Electric vehicles offer numerous advantages, including zero-emission operation, lower maintenance requirements, a comfortable ride, and reduced noise levels. Propelled by electric motors, EVs often necessitate braking operations based on driving patterns and road traffic conditions. While the conventional approach involves the use of mechanical brakes to decrease the EV's speed, this method introduces friction, leading to heating losses and a decline in overall efficiency. To address this, regenerative braking systems (RBS) and energy management systems are implemented alongside mechanical braking, enhancing the overall braking efficiency of the EV system.[3]

1.4 Block Diagram

Real-time optimization methods address global optimization challenges by focusing on local optimization problems within a system. Various techniques, such as model predictive control, artificial intelligent control, robust control, and sliding mode control, are employed for this purpose. Utilizing phase-plane theory and series control technique, and taking into account tire-road friction and vehicle safety considerations, a significant 69.74% energy recovery is attained during braking operations.

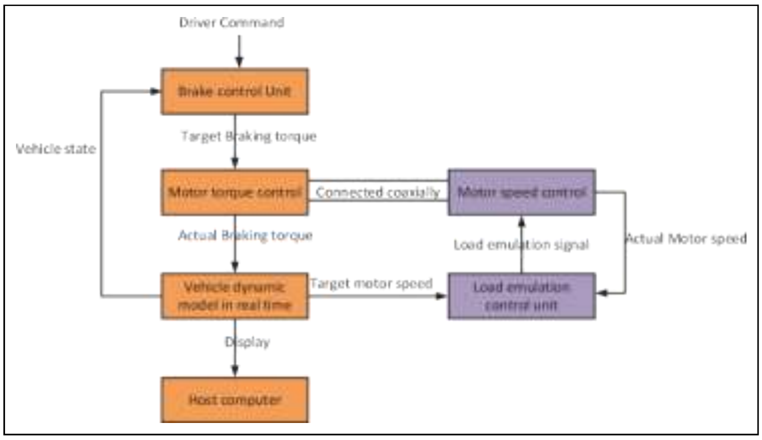

Fig .1 Braking structure of Electric vehicle[3]

The strategy involves seamlessly transitioning between friction and regenerative braking through a sliding mode control mechanism, thereby enhancing the involvement of regenerative braking systems (RBS) to achieve optimal energy recovery levels. The model predictive control technique oversees both the mechanical and regenerative brake systems, leading to a notable improvement in regeneration efficiency, reaching 68.45%. This results in a 5.1% higher efficiency compared to the rule-based control method. By implementing a sliding mode controller to govern the regenerative brake system (RBS) while maintaining wheel slip and tire-road friction within stability limits, there is an 11.4% reduction in braking time. The proposed approach not only enhances vehicle stability by preventing skidding during braking operations but also achieves a smoother braking experience with reduced reliance on mechanical brakes, thanks to the effective coordination of two electric braking.[7]

2. Regenerative braking

The evolving trends in the electric vehicle industry prompt the exploration of advanced techniques to enhance driving efficiency. Regenerative braking involves capturing the kinetic energy from the wheels, which would otherwise be dissipated as heat and friction in traditional braking systems.[4]Regenerative braking, a crucial technology in various electrified vehicles, enhances fuel efficiency by recovering kinetic energy during slowing down. This system is essential in maximizing energy recuperation while ensuring braking safety. The effectiveness of regenerative braking heavily relies on its integration with the vehicle's mechanical braking system and the effectiveness of the brake blending control strategy. This coordination is vital for achieving optimal regeneration efficiency and maintaining the safety of the vehicle's braking system.[8]

2.1 Principle of Regenerative Braking

As a vehicle is in motion, the wheels generate a substantial amount of kinetic energy. Unfortunately, this energy is typically lost as heat and friction during conventional mechanical braking. The regenerative braking technique, however, is an energy extraction process that transforms this kinetic energy into valuable electrical energy, which can then be stored in batteries. Figure 1 illustrates the typical forward driving condition, where the motor moves in the forward direction, resulting in torque that acts in the direction of wheel spinning.[4]

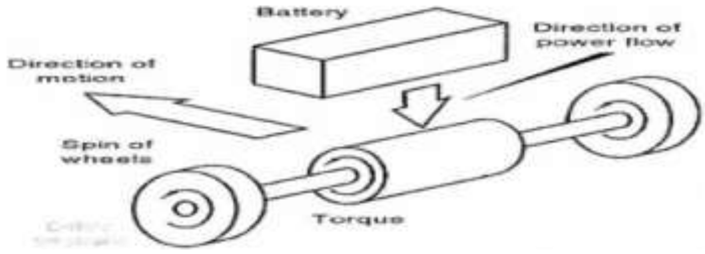

Fig. 2: Normal forward driving condition [4]

The back electromotive force (emf) generated adheres to Lenz's law, opposing the motion of the vehicles. In this scenario, the strengthening magnetic field contributes to an increased vehicle speed profile. Conversely, Figure 2 illustrates the regeneration process during braking, where the motor functions as a generator, causing a reduction in the strength of the magnetic field and subsequently slowing down the vehicle. The motor's torque operates in the opposite direction to the wheel's spinning direction. Notably, the energy is transferred back to the battery during braking, a contrast to the preceding diagram where the battery was the energy supplier. [4]

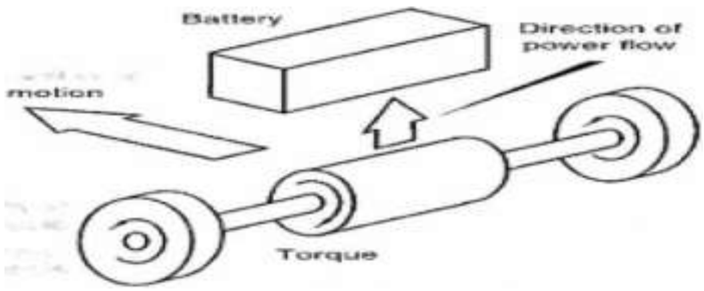

Fig. 3: Regenerative action during braking [4]

Regenerative braking significantly diminishes reliance on traditional fuel sources, fostering greater fuel conservation and emission reduction. Its effectiveness is particularly pronounced in urban settings characterized by frequent stop-and-go driving conditions. Additionally, the regenerative braking system achieves shorter braking times compared to conventional methods, ensuring a quicker halt for the vehicle.[4]

2.2 Advantages of regenerative braking

There are several advantages of regenerative braking taken over the traditional braking system such as:

1. Better control on braking
2. This technique is more efficient during stop and go services mainly in urban regions.
3. Prevents wear and tear on mechanical braking
4. It has better fuel efficiency [4]
5. More control over braking
6. More efficient and effective in stop-and-go driving conditions
7. Prevents wear on mechanical brake systems
8. Better fuel economy
9. Save energy [5]

2.3 Battery management system

Electric vehicles rely on batteries to store and deliver electrical energy, determining the vehicle's range. The state of charge (SOC) of these batteries reflects the amount of stored charge in the system. In the realm of electric vehicles, batteries are characterized by their energy density, reasonably high power-to-weight ratio, and energy-to-weight ratio. The below figure illustrates a comparative analysis of different batteries based on specific energy density and volumetric energy density parameters. Notably, Lithium-ion batteries stand out for their lighter weight, smaller size, and the highest specific energy density.Lead-acid batteries are often preferred due to their cost-effectiveness and reliability. It is crucial not to overcharge the battery beyond its SOC to prevent performance degradation. Interestingly, lead-acid batteries can tolerate voltages above their rated levels without suffering performance setbacks. This dual consideration of energy characteristics and charging practices contributes to the ongoing refinement of electric vehicle battery technology.[4]

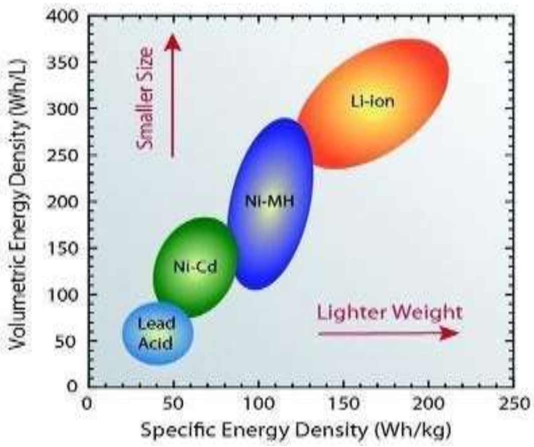

Fig. 4: Comparision of different batteries[4]

2.4 Energy Recovery Process

The energy recovery mechanism involves harnessing kinetic energy from the vehicle's wheels, which is typically lost in traditional braking methods. Through regenerative braking, this otherwise wasted energy is captured and converted into valuable electrical energy, subsequently stored in batteries. This process significantly contributes to extending the overall range of the vehicle.

The kinetic energy contained in the vehicle is given by K.E=1/2mv^2

Where, m is mass of the vehicle and v is the speed with which vehicle is moving.

The optimal extraction of energy occurs when the vehicle operates at speeds surpassing the rated limit, during coasting or on downhill slopes. In such scenarios, there is a risk of the battery voltage exceeding the rated value, potentially causing damage. To mitigate this, a provision is necessary to dissipate excess energy when the battery is fully charged. This involves connecting a resistance across the DC link, where surplus energy is dissipated as heat. Engine losses are directly proportional to speed; therefore, maintaining a lower speed reduces these losses. This, in turn, increases tractive torque, allowing the vehicle to coast for an extended duration. Enhancing fuel efficiency involves maximizing coasting time, particularly when traveling downhill. [4]

2.5 Efficiency calculation:

$E^{*=}$ 1 Pdt
drive $\int a \geq 0$ drive

E drive = E* drive –ηdηaηgenηchargeηdischargeηmηaηdηregen

∆ E drive= E* drive- E drive = ηdηaηgenηchargeηdischargeηmηaηdηregen

σ = ∆ E drive/ E* drive*100%= ηdηaηgenηchargeηdischargeηmηaηdηregen/ E* drive

Where

ηd =efficiency of drive unit ηa =efficiency of axle

ηgen = generation efficiency of the motor ηcharge= charging efficiency of the battery

ηdischarge= discharge discharging efficiency of the battery ηm =motor efficiency

E drive =energy consumption of a vehicle with regenerative braking

E^{*} drive = energy consumption of a vehicle without regenerative braking

E energy consumption of vehicle with regenerative braking

σ =regenerative braking contribution to energy utilization reduction of vehicle Fmot_brk= braking force of motor

Regenerative braking is one of the important systems in electric vehicle since it has the ability to save the wastes energy up to 8-25%. This amount of saved energy can be use to extend our daily journey or to be used to power up the accessories in the car.[6]

3. BRAKE BY WIRE SYSTEM

3.1 BBW system

Electric vehicles (EVs) are widely recognized as a significant trend in the global automotive industry, aiming to enhance tra nsportation safety, reduce environmental impact, and improve overall driving comfort. Within the realm of intelligent connected EVs, the brake -by-wire (BBW) system plays a pivotal role in determining vehicle performance and the effectiveness of braking energy recuperation. As an in tegral component, BBW systems exhibit substantial potential for advancing vehicle braking capabilities, aligning with the growing de mands for enhanced safety and energy efficiency in vehicles. In recent years, these systems have undergone notable transformations in b oth structure and control methodologies, not only bolstering safety and energy recovery efficiency but also incorporating additional functi onalities. The braking control challenges in smart connected electric vehicles (EVs) are marked by several novel aspects: Firstly, there's t he complexity involved in synchronizing electromechanical and hydraulic controls. Secondly, there's a variety of factors that affect effici ency. Thirdly, there's the intricate interplay between information systems and power components. A comprehensive examination of how to effic iently align electromechanical and hydraulic controls during braking in these vehicles is crucial. Such a study will maximize the intellig ence and energy- saving potential of connected EVs, while also ensuring the safety, efficiency, and longevity of their operation. [7] There is no physical mechanical link between the calipers and the brake pedal. Instead, the pedal functions as a simulator. When a driver steps on it, the force is measured by sensors that immediately communicate the braking information to the Brake Control Unit (BCU). The BCU processes this information and sends a command to electro-hydraulic actuators, which converts the command signal into caliper hydraulic pressure/clamping force, which in turn slows or stops the vehicle.

1 motor 2 speed reducer 3 ball screw 4 brake caliper module

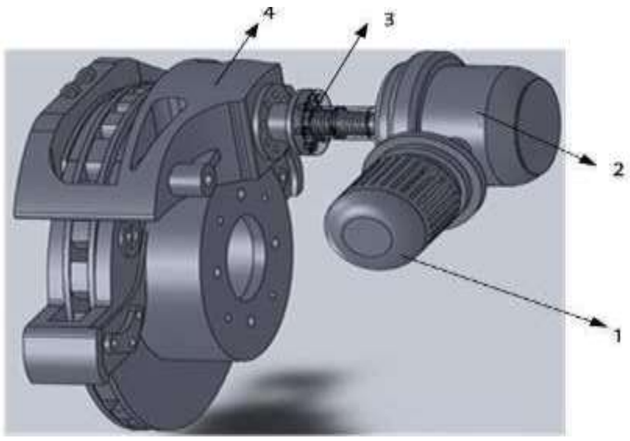

Fig. 5: Structure of brake by wire system[9]

3.2 Framework of Brake-By-Wire System

To satisfy the growing requirements for brake-by-wire (BBW) system performance, ongoing efforts involve continual optimization of system components and advancements in control technology. Regarding component control, current research primarily concentrates on me chanical aspects (power-assisted machinery, brake pads), electrical elements (power-assisted motor, drive motor, battery), and hydraulic components (brake master cylinder, hydraulic valve). These investigations delve into matters such as brake friction, precise control, An ti-Lock Braking System (ABS), and dynamic response. It is crucial to acknowledge the substantial impact of friction on system performance dur ing the braking process.

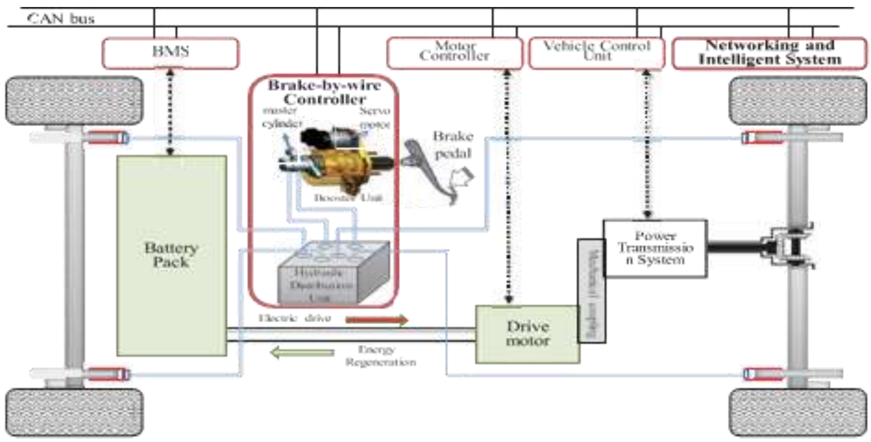

Fig. 6: STRUCTURE OF BBW[7]

The power assist system transforms the force from the motor into thrust to assist in braking by utilizing deceleration, torqu e amplification mechanisms, and motion transfer mechanisms. The friction produced during these mechanical motions, in conjunction with the no rmal force, influences feedback control. Additionally, friction induces a chattering phenomenon during the control of the mechanism. To m itigate the impact of friction in controlling the braking system, efforts are made to eliminate its influence. [7]

This system consists of battery management system (BMS), BBW controller, motor controller, networking and intelligent systems, vehicle control unit, brake pedal,battery pack, drive motor and power transmission system. In this setup, the Battery Management System (BMS) serves as a protective control system for the power battery, consistently monitoring its status to ensure the safety of intelligent connected electric vehicles (EVs). The motor controller, following commands such as gear, throttle, and brake inputs, manages the EV's starting operation, forward and reverse movements, climbing, and assists in braking, with a portion of the braking energy stored back into the power battery. The Brake-By-Wire (BBW) controller comprises essential components like the master cylinder, servo motor, booster unit, and hydraulic distribution unit. During braking, the displacement of the brake pedal and the servo motor increases oil pressure in the master cylinder, distributing appropriate braking force to the wheels through the hydraulic distribution unit. A segment of this braking force is dedicated to friction braking for safety, while the remaining portion is harnessed for regenerative braking, allowing the recovery of braking energy. In this regenerative process, the motor, functioning as a generator, returns a portion of the braking energy back into the power battery.[7]

3.3 Management Approach Of BBW and Energy Recovery

Research in the field of braking systems primarily focuses on two critical areas: braking safety and the recovery of braking energy. When designing a braking system, the primary concern is the vehicle's safety, which includes the ability to reduce speed rapidly and maintain control over the braking direction. To meet these safety standards, it's essential to provide adequate braking force to each wheel and allocate this force effectively. Additionally, enhancing the vehicle's energy efficiency is a key consideration in the design of braking systems, particularly in electric vehicles (EVs). In EVs, there is a coexistence of mechanical friction braking and electric regenerative braking. Various control strategies are developed for this dual-mode braking system. These strategies aim to not only ensure optimal braking performance of the vehicle but also to maximize the recovery of braking energy. However, these two goals often necessitate different distributions of braking force. Consequently, the design of the braking control strategy revolves around striking the right balance between these objectives, based on the situation and desired outcomes.

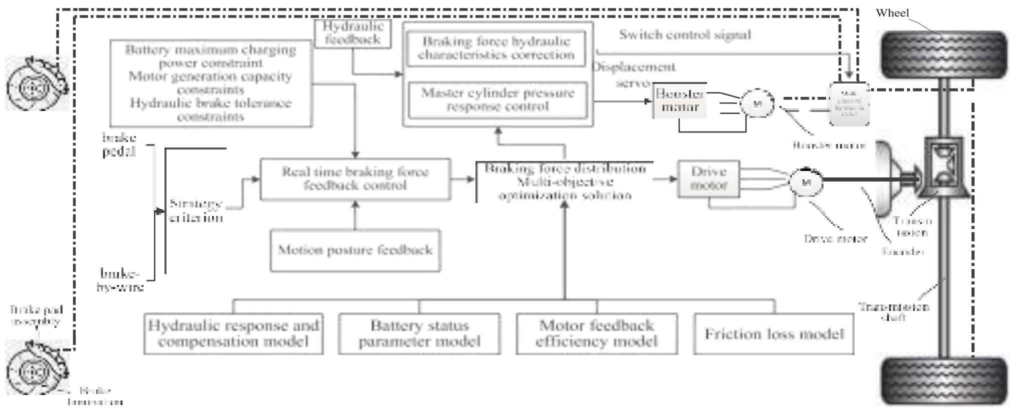

Fig. 7: Management Approach Of BBW[7]

3.4 Braking force Calculation for Front-Rear Wheels

In driving scenarios, it's common for drivers to face situations where an emergency brake is needed while taking a turn. In s uch circumstances, it's crucial to utilize the maximum longitudinal braking force of each wheel to ensure the braking distance remains short. At the same time, the lateral force generated by steering divides the overall friction, which is necessary to accurately follow the curved path. Ho wever, this can reduce the braking effectiveness in the forward direction. The balance between tire -road friction, influenced by adhesion and tire load, creates a compromise between braking efficiency and steering ability. In this study, the principle of prioritizing stability is adopted to address this challenge. This approach involves allocating the longitudinal braking force with the condition that the requirements for late ral force are adequately met. The maximum friction of the front and rear wheels, Fbf and Fbr, are hence computed as follows:[10]

Fbf=μFzf=(c+ZxHg) μG/H Fbr=μFzr=(a-ZxHg) μG/H

where , μ denotes the tire-road friction coefficient , hg represents the height at the center of gravity **,** L is the axle distance

3.5 Issues of BBW System intelligent connected EVs.

BBW (Brake-By-Wire) systems are prone to unexpected failures in operation due to the replacement of traditional mechanical or hydraulic links between the pedal and wheel actuators with cables and wires. This change has led to increased complexity in both the architecture and management of BBW systems. Consequently, there is significant potential for advancement in the integrated control of these systems. Addressing the current technological challenges and fulfilling future requirements for braking performance are key areas for development in this field. Enhancing electric vehicles (EVs) with additional functionalities can significantly boost their performance and energy efficiency, but this also introduces challenges like intricate control mechanisms and structural complexities. To address these issues, system reliability is enhanced through a two-pronged approach: implementing a robust control strategy and streamlining the system by eliminating unnecessary components.

For BBW (Brake-By-Wire) systems managing complex braking interactions, the control strategy must balance safety, reliability, and energy efficiency. This strategy also needs to hormonize the conflicting goals of quick responsiveness and precise control. While a fast-reacting braking system can compromise control accuracy, achieving an optimal balance between quick response and precision is crucial. Additionally, abrupt changes in braking torque can cause discomfort for the driver, a problem that requires further in-depth research.

To mitigate the risk of system failures that could compromise safety, BBW systems employ fault-tolerant technologies. These technologies ensure the system continues to operate safely and maintain performance standards even when some faults occur. Furthermore, the use of real-time vehicle monitoring and diagnostic technologies can identify issues promptly, alerting drivers to address repairs in a timely manner.[7]

4. Energy Recovery Efficiency

To evaluate the energy regeneration performance by the proposed control algorithm during regenerative brake, the regeneration efficiency η parameter, which can be expressed as

$$\eta_{reg} = \frac{E_{reg}}{E_{recoverable}} \times 100\%$$

where *Ereg* is the energy regenerated by the regenerative braking system, *Erecoverable* is the maximum value of the recoverable energy, i.e. them kinetic energy left after subtractingall the energy that would be dissipated by road drag and air resistance.

The regenerated energy is expressed by:

$$E_{reg} = \int_{t0}^{t1} UIdt$$

The recoverable energy by:

$$E_{recoverable} = \frac{1}{2}mv^2 - \int_{t0}^{t1} fmgvdt - \int_{t0}^{t1} \frac{C_D \cdot A}{21.15} \cdot (3.6v)^2 \cdot vdt$$

where *t*0 is the initial braking time, and *t*1 is the final braking time. *U* is the output voltage of battery pack. *I* is the chargingcurrent of battery.[8]

Table 1 –Enhancing regenerative braking energy recovery through integration of brake by wire system

Control strategy	Recoverable energy [kWh]	Regenerated energy [kWh]	Regeneration efficiency [%]	Efficiency improvement [%]
Baseline	39.84	25.87	64.94	-
Proposed	39.98	32.02	80.10	23.36

The regeneration results under normal braking process are shown in table given below. According to data, the regeneration efficiencyof the original control strategy is 64.94%, while the regeneration efficiency of the proposed control algorithm is 80.10%. The improvement of the regeneration efficiency by theproposed control algorithm based on by-wire brake system is above 23%.[8]

The regenerative braking is alone not sufficient for effective braking .Through the integration of brake by wire system in the electric vehicle, there is an improvement in efficiency of the vehicle energy recovery.

Conclusion:

In electric vehicles (EVs), a Brake-By-Wire (BBW) system is not typically used in isolation. Instead, it's often part of a more comprehensive braking system that may include traditional friction brakes and, in many cases, regenerative braking .In EVs, BBW systems are frequently integrated with regenerative braking systems. The BBW system can efficiently control the balance between regenerative and friction braking, optimizing energy recovery while maintaining braking performance. BBW systems in EVs provide improved control and feedback compared to traditional hydraulic systems. They can be programmed to offer a specific pedal feel or response, and they can adjust dynamically based on various driving conditions or modes. regenerative braking Captures and converts kinetic energy into electrical energy, which can be stored in the vehicle's battery for later use. More commonly associated with electric and hybrid vehicles where the recovered energy can be redirected to the battery. Brake by wire system Focuses on electronic control of the braking system, not inherently designed for energy recovery. Can be implemented in various vehicle types, both conventional and electric, to improve overall braking performance.

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