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Advancements in Regenerative Braking: A Novel Circuit Design and Performance Analysis

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Abstract— The ongoing energy crisis and the depletion of natural resources demand the development of cutting-edge technologies designed to reclaim energy that is frequently wasted in contemporary systems. A notable innovation in this area is the regenerative braking system, especially within the automotive sector. This technology enables the conversion of a vehicle's kinetic energy (K.E.) into a usable form, which can either be harnessed immediately or stored for future application. Regenerative braking systems capture a portion of the K.E. dissipated during braking and either store it or revert it to its original form. This recaptured energy is typically stored in batteries or capacitors for later use, or alternatively, it can be stored using a rotating flywheel—recognized as one of the most cost-effective and efficient methods for energy storage and recovery.

This paper presents a simulation of an innovative regenerative braking system that harnesses flywheel inertia to store energy. When the brakes are engaged, the flywheel generates a counteracting force against the wheel's forward motion. A rider-operated clutch mechanism locks the system in place, allowing for the accumulation of energy across multiple braking instances. In electric vehicles, this regenerative braking mechanism repurposes the engine as a generator, channeling the produced electrical power to an external load. This dual-function process not only decelerates the vehicle but also recaptures energy, which is redirected to the load. The proposed approach represents a significant advancement in energy recovery and storage for electric vehicles, enhancing both efficiency and sustainability.

Index Terms— Regenerative Braking, BLDC Motor, MATLAB

I. INTRODUCTION

Regenerative braking systems recuperate energy that is ordinarily dissipated during vehicle deceleration, thereby improving overall energy efficiency. This technology, employed in electric vehicles ranging from motorcycles to automobiles, converts kinetic energy into reusable electrical energy, significantly reducing energy loss. In contrast to conventional disc brakes, which dissipate kinetic energy as heat, regenerative braking leverages the electric motor to function as a generator, capturing and storing energy during braking events.

In electric vehicles, Brushless Direct Current (BLDC) motors, frequently equipped with Hall effect sensors, are widely utilized. These sensors deliver accurate rotor position feedback, facilitating precise control of motor phase commutation. During braking, the BLDC motor functions as a generator, generating back electromotive force (EMF). This regenerated energy is then conditioned and stepped up to a higher voltage for efficient storage within the battery cells. Current research efforts in energy regeneration are focused on optimizing the efficiency and broadening the applicability of these systems, underscoring their potential to significantly elevate the performance and energy efficiency of electric vehicles.

Fig.1: Hardware Implemented Braking System

II. IMPLEMTATION

Brushless DC (BLDC) motors differ fundamentally from conventional DC motors in their operating principles. In traditional DC motors, the system comprises a rotor and a stator. The stator, which is stationary and equipped with field windings, generates a magnetic field of constant amplitude. The rotor, the rotating component, undergoes mechanical commutation through brushes that make contact with the commutator, facilitating continuous rotation by periodically reversing the current direction. Both the stator and rotor are powered by a constant DC voltage.

BLDC motors feature a rotor equipped with permanent magnets and eliminate the need for brushes or a commutator. The stator consists of phase windings and laminated silicon steel sheets, which generate a rotating magnetic field through the sequential switching of these windings. The motor's rotation is driven by the interaction between the magnetic field of the stator and the rotor's fixed magnets. BLDC motors are classified into two main types—inner rotor and outer rotor—depending on their specific application in electric vehicles. Additionally, they are distinguished by the shape of their back EMF waveform, being either trapezoidal or sinusoidal.

BLDC motors, owing to their brushless configuration, eliminate friction-induced heat losses, operate with reduced noise levels, and exhibit a longer operational lifespan compared to traditional DC motors. However, these advantages come with higher costs and increased control system complexity. In this project, a three-phase trapezoidal BLDC motor is employed for simulation.

To ascertain the position of BLDC motors, Hall effect sensors are utilized. Accurate rotor position information is essential for executing the commutation sequence, and this can be achieved either with sensors or via sensorless methods. Sensorless position detection relies on identifying the zero-crossing point of the back EMF, which then informs the commutation sequence. When using Hall effect sensors, they are typically embedded in the stator to detect rotor position. For a three-phase BLDC motor, three sensors are generally sufficient, strategically placed at 60° or 120° intervals. In this project, 120° Hall effect sensors are employed to determine the rotor's position.

The inverter, which consists of semiconductor switches, is responsible for controlling the BLDC motor. These switches facilitate rapid switching operations, with each stator phase being controlled by a pair of switches. The battery, a crucial element in electric vehicles, serves as the primary energy storage unit, providing power to the entire system. During regenerative braking, the battery also captures and stores the generated energy. To effectively charge the battery, a voltage higher than its nominal level is necessary, which is accomplished through the use of boost converters in low-voltage systems.

In simulating regenerative braking for electric vehicles, brake control is crucial for managing the transition between traditional friction braking and regenerative braking. The brake control system decides when to activate regenerative braking, apply traditional friction brakes, or use a combination of both, based on factors such as vehicle speed, driver input, battery state of charge, road conditions, and desired deceleration. The system implements a regenerative braking strategy to maximize energy recovery while ensuring safe and comfortable vehicle operation, modulating regenerative braking based on these factors.

A. Decoder Function in Simulation of Regenrative Braking

In the regenerative braking simulation for electric vehicles, a decoder is an essential element that converts data from one representation to another. Specifically, the decoder translates the electrical signals generated during the regenerative braking process into a format suitable for the simulation software. As the vehicle slows down, the electric motor, functioning as a generator, generates electrical energy as voltage and current signals. The decoder transforms these analog signals into a digital format that can be comprehended and analysed by the simulation software.

Once converted, the simulation software can analyse and process the data to simulate the behaviour of the regenerative braking system. This includes calculations related to energy recovery, battery charging, vehicle dynamics, and other relevant parameters. The decoder also provides feedback to the simulated control system by translating simulated sensor readings into signals usable by the control algorithms. This allows for real-time adjustments to braking force and other parameters.

For accurate representation of the regenerative braking system's behaviour, the decoder is seamlessly integrated into the simulation environment. This involves interfacing with other simulation components such as the vehicle model, the powertrain model, and the battery model.

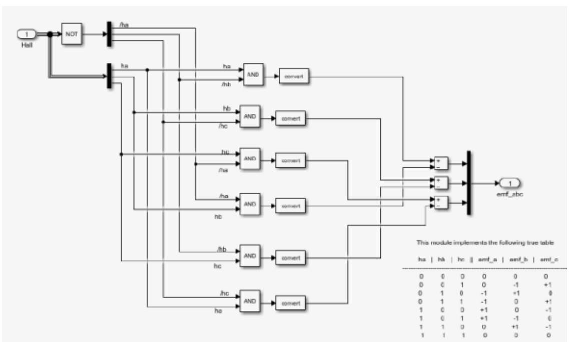

Fig. 2: Decoder Function

A. *Gate function in simulation of regenerative braking*

A gate function is essential for defining the activation threshold of regenerative braking. It can be set to trigger regenerative braking only when the vehicle's speed exceeds a specific limit or when the driver applies sufficient braking force. Moreover, the gate function controls the distribution of energy among the braking system, the electric motor/generator, and the battery pack. It determines when to convert kinetic energy into stored energy in the battery or when to release excess energy.

The gate function integrates with the vehicle dynamics model to ensure that regenerative braking is applied in a manner that preserves stability and control. This includes implementing safety protocols to prevent regenerative braking from inducing wheel lockup or instability under certain conditions. Gate functions are typically tested and optimized within a simulation environment to ensure compliance with performance, efficiency, and safety standards. This process involves performing virtual tests across a range of scenarios to assess the regenerative braking system's effectiveness and to refine control parameters.

In simulation software, gate functions may also involve real-time decision-making processes, as illustrated in Fig. 4. They continuously monitor sensor data and adjust regenerative braking settings on-the-fly to adapt to changing driving conditions and optimize energy recovery.

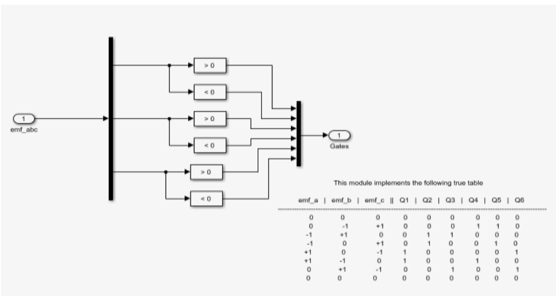

Fig.3: Gate Function

B. *Subsystem simulation of regenerative braking*

In the simulation of regenerative braking for electric vehicles, various subsystems are employed to model and analyse different aspects of the braking system. These subsystems work together to simulate the behaviour of the electric vehicle during braking events. A comprehensive approach involves integrating several key subsystems to accurately model the behaviour and performance of the regenerative braking system.

- Powertrain Model: Simulates the electric motor's operation as both a propulsion source and a generator during braking, alongside the transmission dynamics.
- Battery Model: Captures energy storage dynamics, including state of charge and temperature effects.
- Brake System Model: Incorporates both regenerative braking and traditional friction brakes, ensuring a balanced approach to deceleration and energy recovery.
- Vehicle Dynamics Model: Accounts for mass, inertia, and aerodynamics, providing inputs to the powertrain and brake systems based on vehicle speed and driver inputs.
- Control System: Orchestrates the interaction between the powertrain and brake systems, optimizing energy recovery while maintaining vehicle stability and safety.
- Environment Model: Considers environmental factors such as road grade and traffic conditions.
- Thermal Management Subsystems: Address heat dissipation in components like the electric motor and battery.
- Energy Management Strategy: Governs regenerative braking torque application based on driving conditions and battery state of charge, aiming to maximize energy recovery and system efficiency.

Integrating these subsystems enables engineers to conduct thorough simulations and evaluate regenerative braking performance across a range of scenarios and design parameters.

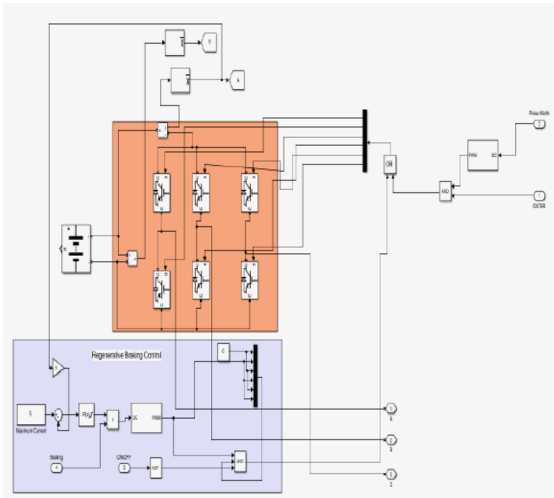

Fig. 4: Subsystem Diagram

IV. SIMULATION OF REGENERATIVE BRAKING FOR ELECTRIC VEHICLE IN MATLAB SIMULINK

After driving the BLDC motor, when a stopping command is issued, the motor stops with its own inertia, producing back EMF. During this time, the regenerative braking system activates, inducing back EMF, which is then rectified and regulated to charge the battery. The voltage level is increased above the battery voltage to facilitate charging.

The data from the motor's m-end after the BLDC motor stops are crucial for regenerative braking. The period between 0-4 seconds represents the energized BLDC motor. After 4 seconds, the motor stops by its own inertia, and regenerative braking begins. As the motor decelerates, voltage is induced in the phases, which must be increased above the battery voltage to store the generated energy.

In MATLAB/Simulink, the back EMF from the BLDC motor is converted into a usable form. Direct connection of the back EMF measured at the m-end of the BLDC motor to circuit elements like resistors or coils is not possible. However, the signal taken from the bus selector can be connected to the control terminals of the blocks. Thus, these data are connected to the control ends of the controlled-voltage sources to simulate the regenerative braking process effectively.

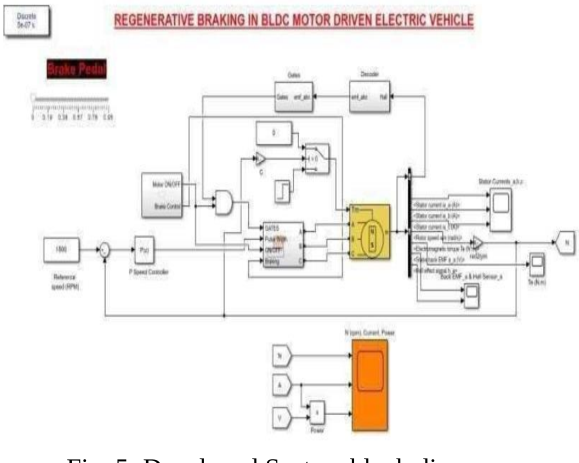

Fig. 5: Developed System block diagram

V. RESULT AND CONCLUSION

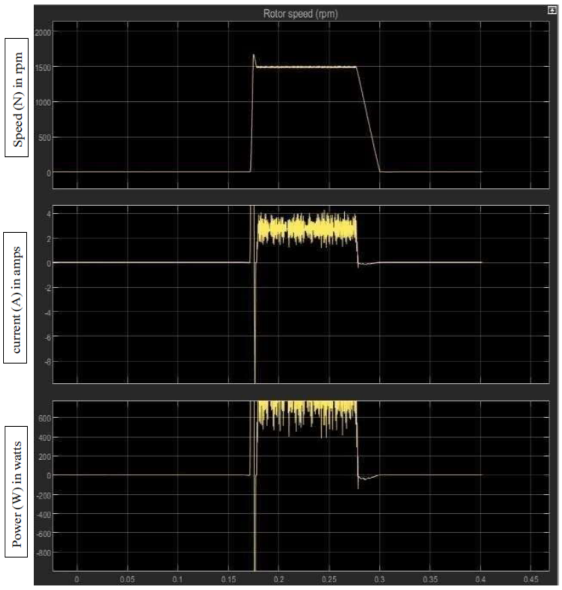

Fig. 6: Simulated Output

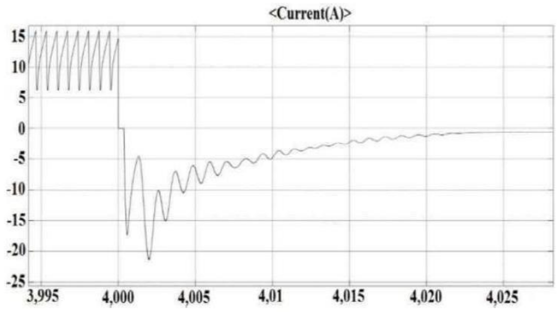

Fig. 7: Battery current charge waveform

The current waveform illustrates the flow of electrical energy throughout the system. Initially, during normal driving conditions, current flows from the battery to the motor to propel the vehicle forward. However, when regenerative braking is initiated, this current flow reverses direction as the motor transitions into a generator, converting kinetic energy into electrical energy. The waveform depicts this reversal of current flow, showcasing the efficient capture and utilization of energy during braking. Simultaneously, the speed waveform reflects the vehicle's deceleration during regenerative braking. As the braking force is applied, the vehicle's speed gradually decreases. This reduction in speed correlates with the conversion of kinetic energy into electrical energy, demonstrating the effectiveness of regenerative braking in slowing down the vehicle while simultaneously recovering energy that would otherwise be lost as heat during traditional braking methods. Furthermore, the power waveform offers valuable insights into the overall energy dynamics of the system. During acceleration, the power waveform typically shows a positive value, indicating the energy consumed by the motor to propel the vehicle. However, during regenerative braking, this waveform may exhibit a negative power value as the motor operates in generator mode, producing electrical energy that flows back into the system.

In this study, a simulation of regenerative braking of BLDC motor that can be used in electric vehicles was carried out in MATLAB/Simulink in detail. For the first 4 seconds of 10 seconds time period, the BLDC motor was powered from the battery. After 4 second, the regenerative braking was applied to the BLDC motor. During the regenerative braking, the BLDC motor was allowed to rotate with own inertia. The generated back EMF value was increased to the upper value of the battery voltage with a boost converter and the battery was charged. As a result of this process, the consumed energy by the BLDC motor was 2446 W/s, the recycled energy was 9.336 W/s and the stored energy in the battery was 8.437 W/s. In other words, 0.38% of the consumed energy in this system with the simulated scenario was recycled and 0.35% of it was stored in the battery for re-use. Regenerative braking can be applied all the electric vehicles. Lots of wasted energy will be recovered with the increasing of electric vehicles in traffic.

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