

Regenerative Braking Assisting Sensor Array for Electric Vehicle

¹Sweta Manjare, ²C. Rajeshwari

¹ Research Scholars, Electrical Engineering Department, NITTTR, Bhopal

² Professor, Electrical Engineering Department, NITTTR, Bhopal

¹ sweta.nitttr@gmail.com

Abstract

As the global automotive industry transitions toward electric mobility, optimizing energy efficiency and driving range remains a primary engineering challenge. The regenerative braking in electric vehicle (EV) assists conversion of the kinetic energy into electric energy which in-turn charges the battery. This action serves to increase the travel range of the vehicle per charging. The traditional RBS setups often suffer from minor delays and inefficiencies in blending mechanical and regenerative braking forces, which can compromise energy recovery. The effectiveness of regenerative braking in EVs depends on various operating factors such as vehicle speed, road and terrain conditions, traffic density, and the driver's driving behaviour. This paper discusses design, development and implementation of a novel sensor array for regenerative braking assisting for EV. The sensor processes the data of sensor array comprising of sensing devices for speed, terrain, brake switch, accelerator, gyro and brake paddle pressure. A dedicated control algorithm processes this data and along with SOC of the battery to enable the regenerative braking as well as control the strength of regenerative braking. The experimental results are presented by installing this developed sensor on a customised electric bike which shows 6% more energy recovery in comparison with conventional non dedicated regenerative braking sensor assisted system.

Keywords: regenerative braking, electric vehicle, SOC, energy recovery, sensor array

I. Introduction

The global automotive sector is undergoing a massive paradigm shift toward sustainable transportation, driven by the critical need to curb greenhouse gas emissions and reduce fossil fuel dependency. EVs have emerged as the primary alternative to conventional internal combustion engine vehicles due to their zero tailpipe emissions, low noise profiles, and high tank-to-wheel energy efficiency [1]. Despite these environmental and architectural advantages, driving range anxiety and high cost of large-capacity battery packs are barring the widespread

adoption [2]. To overcome these challenges, engineers are focusing on maximizing on-board energy conservation through intelligent subsystems. The regenerative braking system is a critical technology for enhancing the travel range of EV. In traditional EVs, mechanical friction brakes (liners / drum / disc) are used for deceleration. In case of friction braking, the kinetic energy of moving vehicle is lost to the environment in the form of heat [3]. The motors used in EV are capable of producing electricity when driven with prime mover. During deceleration of the vehicle, the motor operates as a generator and converts kinetic energy of vehicle into electric power [4]. This recovered energy is subsequently routed through power converter to recharge the battery pack [5]. Several researchers have reported that the energy recovery achieved through optimized regenerative braking ranges from 8% to over 25% of the total energy consumption. This variation is largely determined by the driving conditions and the regenerative braking control technique [6 – 9].

The implementation of regenerative braking requires careful coordination between mechanical braking and regenerative braking for vehicle stability, passenger comfort, and safety [10]. Traditional regenerative systems rely on rule-based or static lookup tables governed by coarse vehicle inputs like overall speed or basic throttle position [1], [6]. These methods suffer from severe input latency, failing to dynamically capture the driver intent at the initial moment the brake pedal is depressed. Consequently, a substantial portion of kinetic energy is lost during the transient phase of braking or the transition feels jerky to the driver, compromising ride quality.

In electric two wheelers BLDC motor is commonly deployed. To incorporate the regenerative braking, a bidirectional power converter is demanded in the drivetrain. The power electronics drivetrain interface is regulated motoring and braking mode operation [11]. Essentially, a bidirectional DC-DC converter is implemented for efficient energy transfer during regenerative braking with current controller [12]. The recovered energy during vehicle movement with appropriate control method, converter topologies and use of storage technologies help to increase the energy efficiency and extend the battery life. The innovative frontiers like SiC and GaN for high efficiency and trends in automotive electronics [13] for EVs, AI, and GPS-based traffic control, and driver's behavior model predictive [14] algorithm are also evident.

Retrofitting in ordinary automobiles is made possible by a microcontroller-based smart regenerative system that employs an accelerometer, ultrasonic sensor, motor driver, and hall-effect sensor for energy recovery [15]. For EVs and HEVs, adaptive brake control techniques

with real-time sensor data processing [16] appear potential for increasing range and energy recovery. In order to prevent collisions and accidents, autonomous braking using ultrasonic sensor-based obstacle detection [17] works well. Tilt and gyro sensors [18] are useful for determining the vehicle's orientation as well as its acceleration and deceleration circumstances. Regenerative braking mechanisms can be developed with the use of this sensor data [19].

A smart regenerative braking sensor shall integrate sensors for monitoring vehicle driving condition [20]. This paper discusses a novel regenerative braking assisting sensor that monitors the data from sensor array (speed, terrain, brake switch, battery SOC, obstacles range in front etc.) and assists the main EV controller for seamless transition between motoring and regeneration modes. The developed sensor produces flagged output for managing the strength of regenerative braking. The sensor array data is with time stamp is stored in EPROM memory that can be assessed for future diagnosis and improvements. The experimental results are obtained by installing the developed sensor on customised electric bike and recording the SOC of the battery, status flags and sensor array data.

II. Practical Requirements for Regenerative Braking

The effective implementation of a regenerative braking system requires several essential conditions and system components. The foremost requirement is that the vehicle must possess sufficient kinetic energy, as electrical energy can only be recovered while the vehicle is in motion. During deceleration, the rotational energy available at the wheels and axles is converted into electrical energy by operating the traction motor as a generator. The recovered electrical energy should either be supplied directly to the electrical load or stored in the battery for subsequent use. Consequently, regenerative braking establishes a reverse power flow from the electric motor to the battery, whereas during normal propulsion the power flows from the battery to the motor. Therefore, the power electronic converter employed in the drivetrain must be capable of supporting bidirectional power transfer. In addition, the converter should provide controllable operation in both charging and discharging modes to regulate the energy flow efficiently, thereby ensuring safe and effective energy recovery under varying operating conditions.

In addition to vehicle momentum, operating speed plays a crucial role in the effectiveness of regenerative braking. For most traction motors, like PMDC, BLDC and induction motors, the generated EMF is directly proportional to the rotational speed when the machine operates in

generator mode. Consequently, efficient energy recovery over a wide speed range requires the power converter to operate reliably in both buck and boost modes with robust control. The regenerative braking capability is influenced by several real-world factors, such as driver behaviour, traffic conditions and road terrain. Among these, downhill driving combined with sufficient vehicle momentum provides the most favourable conditions for maximizing energy recovery, as a larger amount of kinetic and potential energy can be converted into electrical energy and stored in the battery.

Regenerative braking systems must also include fail-safe mechanisms that ensure conventional braking remains available in the event of regenerative system failure. The regenerative system failures shall not compromise the vehicle's ability to meet prescribed secondary braking performance requirements.

III. Regenerative Braking Assisting Sensor

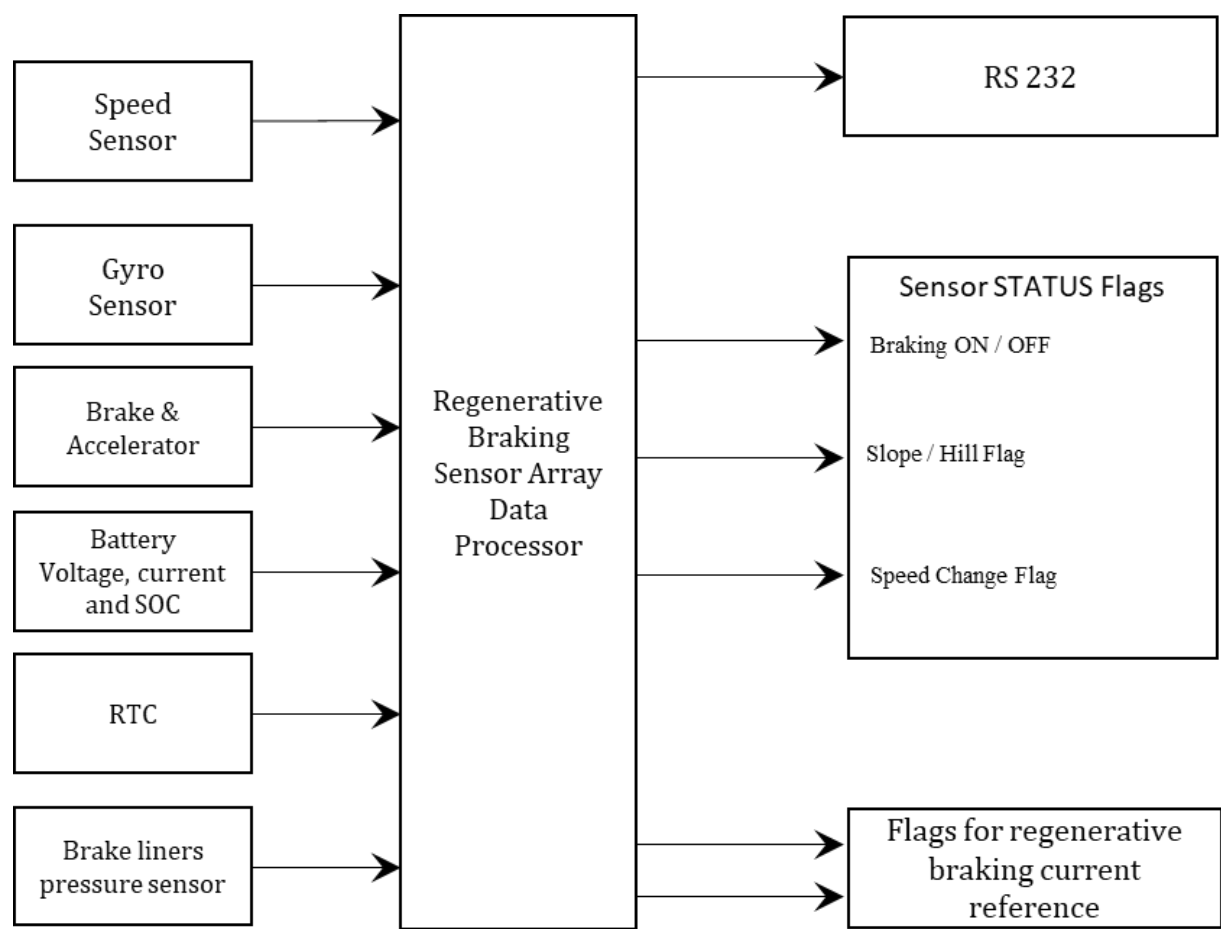


Figure 1: Block diagram of smart regenerative braking sensor

Figure 1 illustrates the block diagram of the proposed smart regenerative braking sensor. The system acquires input signals from the sensors array of speed, gyro, battery status, brake actuation and accelerator throttle position. These sensor signals are processed by a dedicated data processing unit, which analyses the operating conditions and generates seven digital flags. Two out of these seven flags are used for setting the current reference value of bidirectional converter which in-turn controls the strength of regenerative braking. Third flag is set for enabling or disabling regenerative braking. Fourth and fifth flag for indicating the terrain conditions in terms of slope or hill. And sixth and seventh flag to indicate the speed change i.e. increase or decrease in speed in last five seconds. This operational status of the regenerative braking assisting sensor is fed to the main EV controller through serial communication. The technical specifications of the proposed regenerative braking assisting sensor are mentioned in Table 1, while the detailed operational sequence is illustrated in the flowchart of Figure 2. The figure 3 illustrates the interface between regenerative braking sensor and EV powertrain controller.

Table 1: Specification Table

Particulars	Description
Controller	STM32F103C8T6
Speed sensor	Magnetic pickup
Tilt sensor	GYRO MPU 6050 3 axis
Accelerator and brake	Twist throttle accelerator Magnetic switch
Communication	Serial:115200 Bluetooth: HC-05
FLAGS	Regenerative braking ON / OFF Terrain (Slope / Hill) Speed Change (positive / negative)
Voltage sensor	Voltage divider
Current sensor	ACS712
SOC Estimation	Coulomb Counting
Battery	36V 7Ah Lithium Ion Battery
Data logging	EEPROM
Sensor array data display	Android App - Bluetooth Electronics

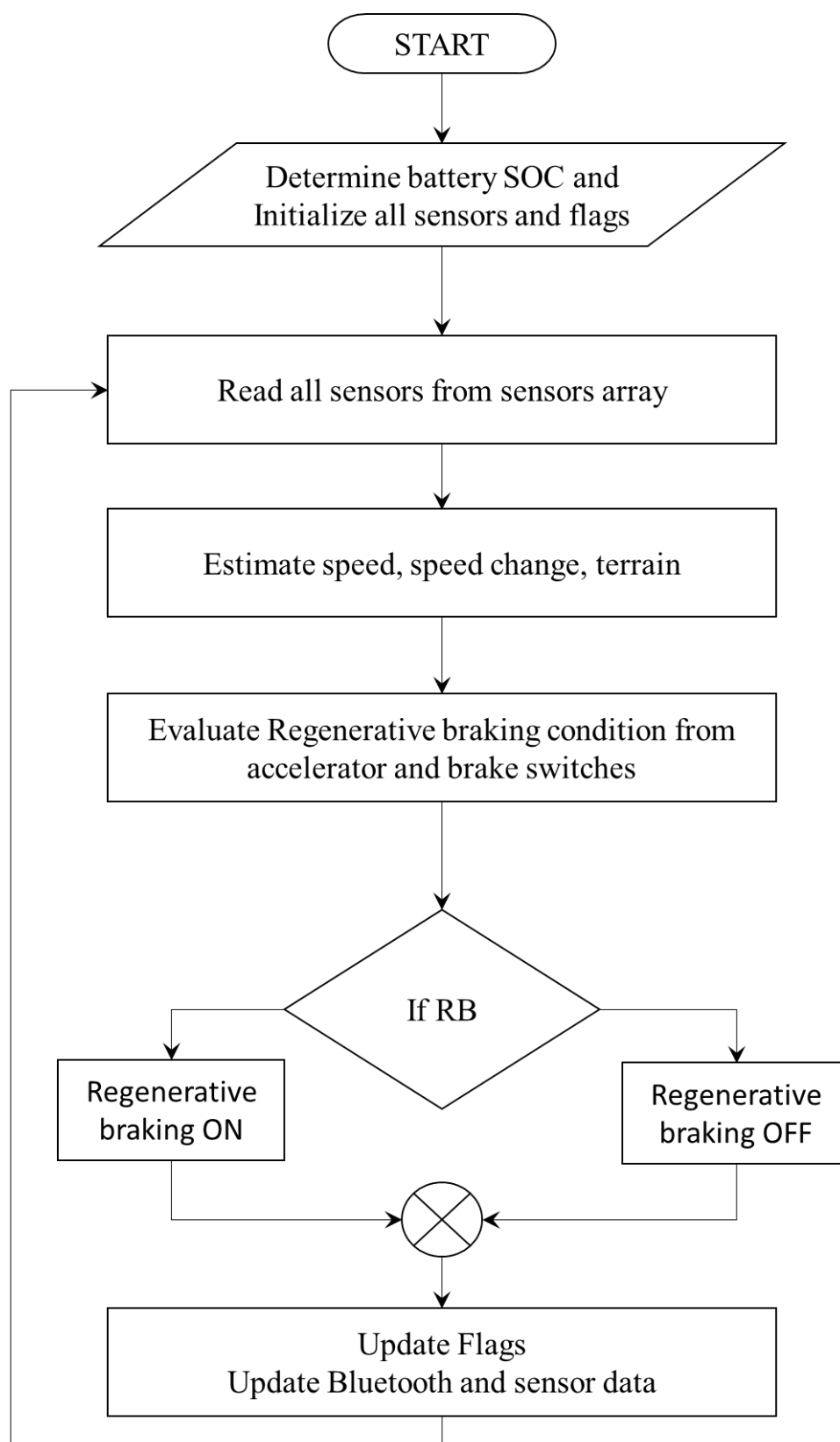


Figure 2: regenerative braking sensor work flow

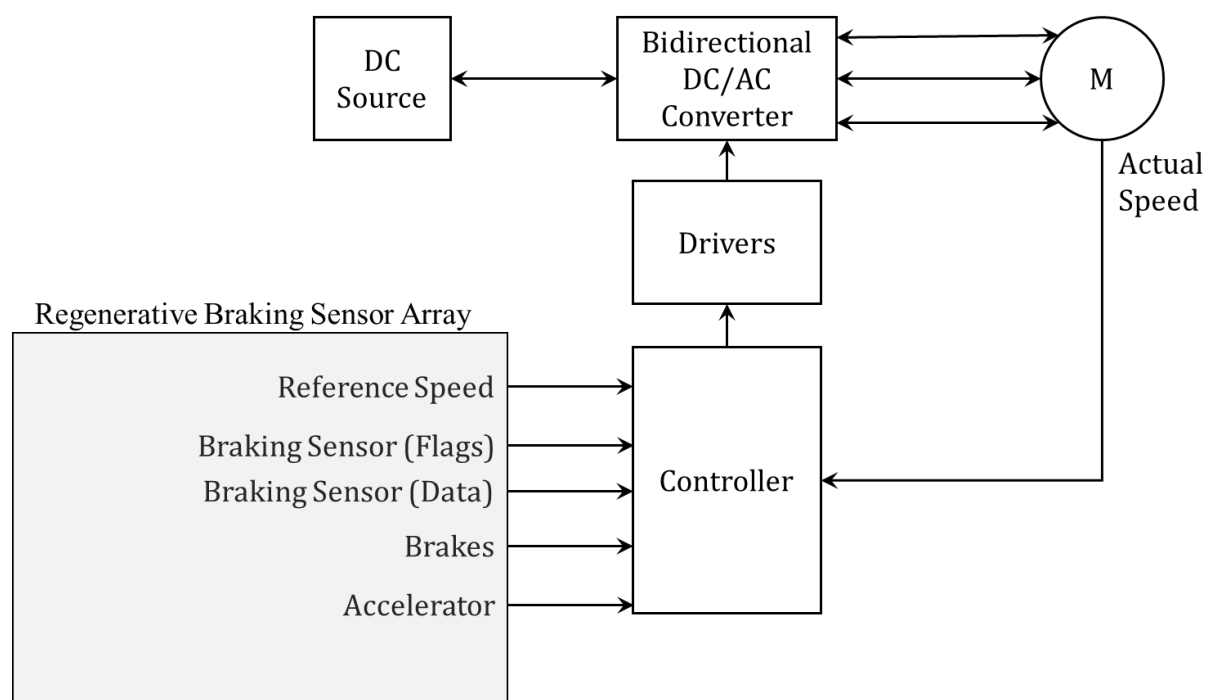


Figure 3: block diagram of EV control system with regenerative braking assisting sensor

The regenerative braking assisting sensor continuously monitors the sensor array and determines change in speed, terrain conditions, braking and accelerating status. At first battery SoC estimation is done by using the data of voltage and current sensors. When the SoC of the battery goes below 85%, then only the regenerative braking assisting sensor is activated. In case the SOC greater than 85%, the regenerative braking stays disabled. This prevents the over voltages in lithium ion battery cells. In case when the vehicle is running on flat terrain or climbing up the hill, the regenerative braking sensor outputs a signal to turn off the regenerative braking system. In case when the vehicle is running on the slope, running with sufficient speed or being decelerated, the regenerative braking assisting sensor outputs a signal for enabling the regenerative braking. The data of the brake liners pressure sensor is also taken as one of the input for determining the strength of regenerative braking. The strength of braking increases with increase in current drawn from the generator.

The entire sensor array data and estimated values of speed change, braking pressure, terrain data, brake switch and accelerator throttle are communicated by regenerative braking assisting sensor to the EV controller through UART at the baud rate of 115200 bits/second. The EV controller processes this data for seamless transition between motoring and regeneration modes. The photographs of developed regenerative braking assisting sensor installed on

customised electric bike is shown in figure 4 and that of the installation on electric bike is shown in figure 6. The user interface for monitoring of the sensor array and flags is constructed through Android based Bluetooth Electronic App. The screenshot of this app during running condition is seen in figure 5.



Figure 4: Photograph of electric bike with regenerative braking assist sensor installation

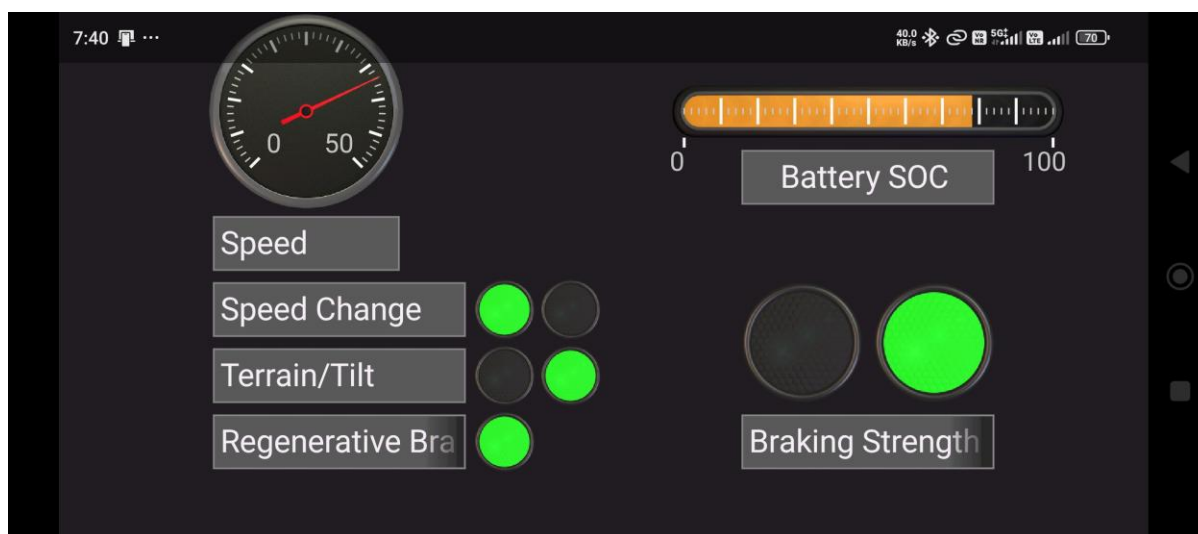


Figure 5: Screenshot of Android Bluetooth Electronic App showing sensor data

IV. Experimental Results

At the start of experimentation, the EV battery is charged up to 80% i.e. a level below the enabling threshold level of regenerative braking. To switch between the motoring mode and regeneration mode, the data of accelerator and brake switch is considered. The regenerative braking is enabled only if the accelerator is completely off. The actual speed of the vehicle is also clubbed to this primary condition and the developed sensor processes the actual speed and

change in speed over a sample time of 3 seconds. The sampling times for each of the parameter responsible for regenerative braking is mentioned in table 2.

Table 2: Sampling periods of sensor parameters

Parameter	Sampling Period (Seconds)	Signal Purpose
Accelerator Throttle	0.5	Transition from motoring to regeneration
Brake switch	0.5	Transition from motoring to braking
Speed	3	Quantifies actual deceleration rate
Speed Change	3	Quantifies actual deceleration rate
Terrain / Tilt	1	Road inclination
SOC	5	Safety gate to prevent overcharging
Flags	1	Indication of sensor array operating conditions and control signal to EV controller

The system of customised electric bike with regenerative braking sensor array was subjected to a practical on road testing conditions. This on road testing included the charging of battery to 80% SOC level and then running the vehicle with conventional controller system and developed system of EV controller integrated with regenerative braking assisting sensor array for a distance of 10 km. It is to be noted that in both the cases of experimentation, the same speed was maintained throughout the range in each case. The experimentation was repeated for five times and average observation results are mentioned in table 3 for conventional controller system and table 4 for the developed system of smart regenerative braking assisting sensor array integrated with EV controller.

The conventional EV controller takes inputs from brakes, accelerator and actual speed to enable or disable the regenerative braking. The table 3 shows the observations during the 10 km run of the bike. The status of accelerator, braking, battery SOC and regenerative braking is indicated at an interval of 0.5 km. The table 4 shows the observations when the same bike with integrated regenerative braking assisting sensors array is integrated. It additionally takes the data of change in speed (in terms of positive or negative) and terrain conditions from tilt sensor (in terms of flat / positive / negative slope) for decision making of regenerative braking ON / OFF operation.

Table 3: Observation Table for conventional system

Distance Traveled (km)	Speed (kmph)	Accelerator	Brakes	Battery SOC	Regenerative Braking
0	0	0	0	80	OFF
0.5	20	ON	OFF	78	OFF
1	35	ON	OFF	77	OFF
1.5	30	OFF	OFF	75	OFF
2	35	ON	OFF	74	OFF
2.5	35	OFF	ON	74	ON
3	40	ON	OFF	72	OFF
3.5	40	OFF	ON	73	ON
4	35	OFF	OFF	71	OFF
4.5	40	ON	OFF	69	OFF
5	35	OFF	ON	70	ON
5.5	40	ON	OFF	69	OFF
6	40	ON	OFF	67	OFF
6.5	35	OFF	ON	68	ON
7	35	ON	OFF	66	OFF
7.5	40	ON	OFF	64	OFF
8	35	OFF	ON	65	ON
8.5	35	ON	OFF	63	OFF
9	40	ON	OFF	61	OFF
9.5	30	OFF	ON	61	ON
10	20	ON	OFF	59	OFF

Table 4: Observation table (developed system)

Distance travelled (km)	Speed (kmph)	Speed change	Tilt	Accelerator	Brakes	Battery SOC	Regenerative Braking
0	0	0	Flat	OFF	OFF	80	OFF
0.5	20	Positive	Flat	ON	OFF	78	OFF
1	35	Positive	Positive	ON	OFF	77	OFF
1.5	30	Negative	Negative	OFF	OFF	76	OFF
2	35	Positive	Flat	ON	OFF	75	OFF
2.5	35	Negative	Negative	OFF	ON	76	ON
3	40	Positive	Flat	ON	OFF	74	OFF
3.5	40	Negative	Flat	OFF	ON	75	ON
4	35	Negative	Negative	OFF	OFF	75	ON
4.5	40	Positive	Flat	ON	OFF	73	OFF
5	35	Negative	Flat	OFF	ON	73	ON
5.5	40	Positive	Positive	ON	OFF	72	OFF
6	40	Positive	Flat	ON	OFF	70	OFF
6.5	35	Negative	Flat	OFF	ON	71	ON
7	35	Positive	Flat	ON	OFF	69	OFF
7.5	40	Positive	Flat	ON	OFF	67	OFF
8	35	Negative	Negative	OFF	ON	68	ON
8.5	35	Positive	Flat	ON	OFF	67	OFF
9	40	Positive	Flat	ON	OFF	65	OFF
9.5	30	Negative	Negative	OFF	ON	66	ON
10	20	Negative	Flat	ON	OFF	65	OFF

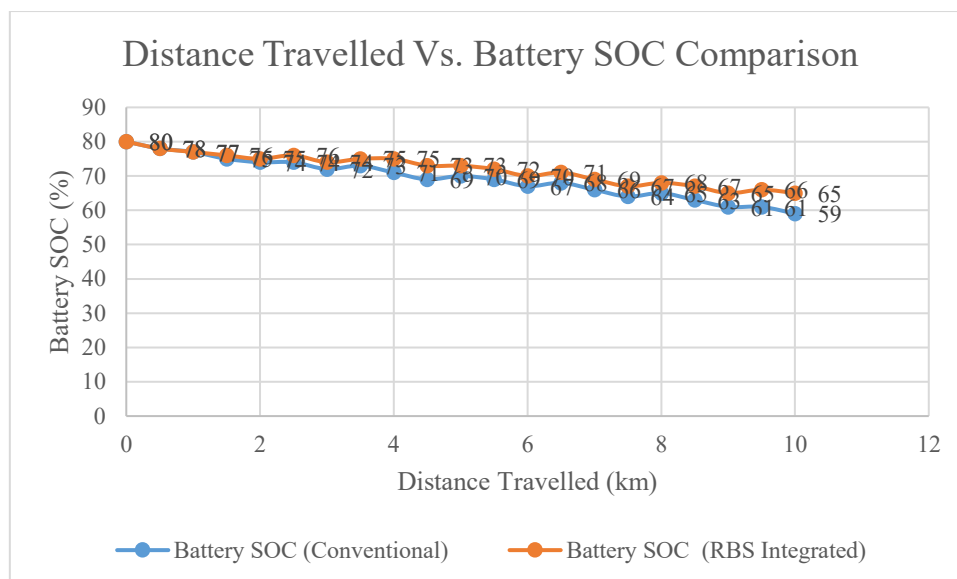


Figure 6: Comparison of battery SOC vs. distance travelled with conventional and regenerative braking assisting sensor array

The figure 8 shows the SOC level of battery in two experimental runs of the bike with run with conventional EV controller and with regenerative braking assisting sensor array. The conventional controller returns battery SOC of 59% after trailing of 10 km distance. On the other hand the proposed system with integrated regenerative braking assisting sensor array yields battery SOC of 65% at the end of 10 km distance travel under same road conditions.

V. Conclusion

The regenerative braking provides key benefits of travel range improvement of electric vehicle. The integration of smart regenerative braking sensor can reduce wear and tear of mechanical braking components as well. The developed regenerative breaking assisting sensors communicates the operational data of actual driving conditions to the EV controller and generates control signals for regenerative breaking. The data of brake switch, throttle, braking pressure, terrain, SOC, speed and speed changes is logged into memory and further be used for analysing driver behaviour. The experimental results shows 6% more energy retention in comparison with traditional system. As advancements in EV technology continue, regenerative braking sensors are expected to be smart, accurate, efficient and indispensable in the development of sustainable mobility solutions.

References

- [1] E. M. Szumska, "Regenerative Braking Systems in Electric Vehicles: A Comprehensive Review of Design, Control Strategies, and Efficiency Challenges," *Energies*, vol. 18, no. 10, p. 2422, 2025.

- [2] Z. Prakash, "Integration of AI and ML in regenerative braking for electric vehicles: a review," *Frontiers in Artificial Intelligence*, vol. 8, pp. 1–15, 2025.
- [3] G. Xu, W. Li, K. Xu, and Z. Song, "An Intelligent Regenerative Braking Strategy for Electric Vehicles," *Energies*, vol. 4, no. 9, pp. 1461–1477, 2011.
- [4] W. Chueprasert and D. Phaoharuhansa, "Study of Regenerative Braking System and Brake Force using Pulse Width Module," *MATEC Web of Conferences*, vol. 306, p. 01004, 2020.
- [5] A. Verma, P. Singh, D. Tongbram, and Y. Rana, "Regenerative braking implementation in BLDC motors for electric vehicle sustainability," *AIP Conference Proceedings*, vol. 3253, no. 1, p. 020012, 2025.
- [6] C. Li, L. Zhang, S. Lian, and M. Liu, "Research on regenerative braking control of electric vehicles based on game theory optimization," *Science Progress*, vol. 107, no. 2, pp. 1–22, 2024.
- [7] S. Lakshmi Prasad and A. Gudipalli, "Optimal Energy Consumption Control Strategy for Electric Vehicle," in *IEEE Access*, vol. 12, pp. 197734-197747, 2024, doi: 10.1109/ACCESS.2024.3512188.
- [8] S. Banerjee, M. Pahwa, S. Agarwal and S. Gupta, "Empowering Tomorrow's Mobility: The Role of EVs in Sustainable Development," *2024 1st International Conference on Sustainability and Technological Advancements in Engineering Domain (SUSTAINED)*, Faridabad, India, 2024, pp. 1001-1007, doi: 10.1109/SUSTAINED63638.2024.11074170.
- [9] A. U. Rehman, S. -W. Ryu, H. Park and J. -W. Jung, "A Critical Review of Recent Industrial Developments, Trends, and Future Perspectives of Power Electronic Systems: Fuel Cell Electric Vehicles," in *IEEE Transactions on Industrial Informatics*, vol. 20, no. 4, pp. 6060-6074, April 2024, doi: 10.1109/TII.2023.3347736.
- [10] T. Payarou and P. Pillay, "Integrated Multipurpose Power Electronics Interface for Electric Vehicles," in *IEEE Transactions on Transportation Electrification*, vol. 9, no. 2, pp. 2429-2443, June 2023, doi: 10.1109/TTE.2022.3209098.
- [11] R. Kannan, P. K. K. C, N. M. Nor and S. Gandhi A, "Design and Simulation of a Bidirectional DC-DC Converter with PI Controller for Regenerative Braking in Electric Vehicles," *2023 IEEE Conference on Energy Conversion (CENCON)*, Kuching, Malaysia, 2023, pp. 64-69, doi: 10.1109/CENCON58932.2023.10369135.
- [12] C. P. Ragasudha and S. Hemamalini, "Performance Analysis of a High Gain Bidirectional DC-DC Converter Fed Drive for an Electric Vehicle With Battery

- Charging Capability During Braking," in *IEEE Access*, vol. 12, pp. 14499-14511, 2024, doi: 10.1109/ACCESS.2024.3357726.
- [13] J. P. Trovão, "Automotive Electronics: Key System Components [Automotive Electronics]," in *IEEE Vehicular Technology Magazine*, vol. 18, no. 2, pp. 113-121, June 2023, doi: 10.1109/MVT.2023.3260544.
- [14] Y. He, S. Fan, K. Hyun Kwak and Y. Kim, "Personalized Automated Braking for One-Pedal Driving in Electric Vehicles Using Model Predictive Control," in *IEEE Transactions on Transportation Electrification*, vol. 11, no. 1, pp. 3215-3228, Feb. 2025, doi: 10.1109/TTE.2024.3435998.
- [15] deshमुख, Pritam & Suryawanshi, Prof & Pisal, Krushna & Rathod, Suraj & Gaikwad, Vijayant & Waghire, Aditya, "Review Paper on Smart Regenerative Braking in E-Vehicle using Microcontroller", *International Journal of Advanced Research in Science, Communication and Technology*. 2022, pp. 610-614. 10.48175/IJARSCT-3982.
- [16] G. Gupta et al., "Intelligent Regenerative Braking Control with Novel Friction Coefficient Estimation Strategy for Improving the Performance Characteristics of Hybrid Electric Vehicle," in *IEEE Access*, vol. 12, pp. 110361-110384, 2024, doi: 10.1109/ACCESS.2024.3440210.
- [17] K. V. Narayana Reddy, S. Vinoth John Prakash, M. Haseeb, S. Sohtun, S. Amosedinakaran and S. Ramesh, "Implementation of Automatic Braking System in Electric Vehicles," *2025 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS)*, Bhopal, India, 2025, pp. 1-5, doi: 10.1109/SCEECS64059.2025.10940793.
- [18] S. M. S, A. George, B. R, S. Chandrachoodan and P. J. Paul, "Multi-Sensor Based Regenerative Charging for Electric Vehicles," *2023 International Conference on Circuit Power and Computing Technologies (ICCPCT)*, Kollam, India, 2023, pp. 253-258, doi: 10.1109/ICCPCT58313.2023.10245584.
- [19] J. P. Trovão, "Innovations Shaping the Future of Automotive Electronics," *IEEE Vehicular Technology Magazine*, vol. 19, no. 2, pp. 94-102, June 2024, doi: 10.1109/MVT.2024.3387248.
- [20] Wawan Purwanto, Dani Hermanto, Ali Basah Pulungan, Padilah Hannum Simbolon, Yolana Nursyafti, "Implementation of Regenerative Brake System Controller by Using Mini Controller Arduino", *TEM Journal*. Volume 13, Issue 3, pages 1751-1757, 2024 DOI: 10.18421/TEM133-03