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Prototyping Of Regenerative Braking System Based On Hybrid Energy Storage System In Electric Vehicle Prototype E-Trail Bangkits

Maulana Ray Romadhon HS[1], Bambang Sudarmanta[1]*
[1]Department of Mechanical Engineering, ITS, Sukolilo Surabaya 60111, Indonesia

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Abstract

The use of a Hybrid Electrical Energy Storage System (HESS) using a battery and supercapacitor in the regenerative braking system on the BANGKITS E-Trail prototype has the potential to offer greater power density and cycle life. The study aimed to maximize the recovery of energy during braking using the system while improving the performance of E-Trail BANGKITS. The proposed regenerative braking system based on HESS was designed and fabricated while considering energy recovery capacity, and maximum electrical load. After fabrication, the system was tested for its efficiency, in energy recovery and to drive the vehicle using recovered energy. The tests were conducted in two steps, which are stationary, and dynamic tests, using a variation of motor and vehicle speed. The results of the tests showed in regenerative mode, the system can recover up to 4410 J of energy with 41% efficiency with ascending trend as motor speed increases, while in drive mode, the system can successfully drive the vehicle at 1430W power draw, and 14.8s of discharge time. In the vehicle performance test, the system was capable of generating a braking force of 427.92N at 36% braking contribution. The system can also extend the driving range of the vehicle by 2.4% of the test route distance.

Keywords: HESS, Regenerative Braking, Supercapacitor, E-Trail

1. Introduction

The development of Electric Vehicle (EV) technology, particularly the incorporation of regenerative braking facilitated by Brushless DC (BLDC) motors, has been a focal point in academic discussions [1]. While lithium-ion (Li-ion) batteries are commonly used as the Energy Storage System (ESS) in EVs, they exhibit drawbacks such as low power density, a narrow operating temperature range, and limited cycle life [2]. The use of Li-ion batteries in regenerative braking raises concerns about potential damage and reduced lifespan due to deviations from specified operational conditions of EVs [1].

To address these challenges, Hybrid Energy Storage Systems (HESS) have emerged as a promising solution for EVs. HESS integrates batteries as the primary energy source and supercapacitors for energy storage during acceleration and deceleration, employing various topologies like passive parallel, cascade, and shared bus [2, 3]. Supercapacitors, distinguished by their large capacitance, higher energy density, longer cycle life, and wider temperature range compared to batteries, present a viable alternative [4].

Several studies have explored the construction of Hybrid Energy Storage System (HESS)-based regenerative braking systems, including works by Carreira et al., 2014 [2], Naseri et al., 2016 [4], Nian et al., 2014 [5], Firmanto et al., 2021 [6], and Suyanto et al., 2023 [7]. Suyanto et al., 2023 [7], specifically proposed a regenerative braking system for GESITS electric motorcycles utilizing HESS supercapacitors while employing fuzzy and PID control methods. The system incorporated a Four Switch Buck-Boost Converter (FSBB) and Power Transfer (PT) circuit to regulate current into the HESS. Fuzzy PID control was utilized to manage the PT circuit, ensuring control over regenerative current and braking force based on parameters like brake lever input, vehicle velocity, and supercapacitor State of Charge (SOC). The fuzzy control design, compared with MATLAB Fuzzy Designer™, exhibited an error of 1.44%. PID tuning using the ITAE method resulted in specific parameters: rise time of 3.33 seconds, settling time of 3.11 seconds, overshoot of 9.20%, and steady-state error of 2.2%.

The studies mentioned above have presented various regenerative braking systems, each with its distinct advantages and limitations. However, none of the referenced research has comprehensively explored the application of regenerative braking systems, along with a complete performance analysis, in an electric motorcycle. Furthermore, the utilization of a Hybrid Energy Storage System (HESS) configuration in such systems has not been proposed.

To address this gap, this research introduces a regenerative braking system based on HESS configuration designed for implementation in the EV prototype E-Trail

*Corresponding author. Email: sudarmanta@me.its.ac.id

BANGKITS motorcycle. The study aims to thoroughly analyze the proposed system, covering aspects such as system design, performance analysis, and its impact on the overall performance of the EV prototype E-Trail BANGKITS.

2. Experimental/theoretical method

2.1. Plant identification

The plant identification was carried out by directly examining the object of research, the EV prototype E-Trail BANGKITS. After plant identification was carried out, the following specification for E-Trail was acquired, which is listed in Table 1 below.

2.2. Plant identification

The total energy potential obtainable from vehicle braking is defined as the entire energy dissipated from the reduction of kinetic energy originating from a moving vehicle, formulated in Equation 1 as follows.

$$E_k = \frac{1}{2} m v^2 \tag{1}$$

where m and v respectively stand for vehicle mass and initial velocity.

When regenerative braking occurs in an electric motor, a phenomenon takes place where the Brushless Direct Current (BLDC) motor, which normally functions as a driver, is in turn driven by the transmission system when the vehicle is coasting. This causes the BLDC to shift its function from a motor to a generator capable of generating electricity while also turning it into an electromagnetic brake [8]. This phenomenon is referred to as regenerative braking. When a BLDC motor switches its function to a generator, the power generated at a specific RPM cannot be equated with the power consumption of the BLDC at the same RPM when it operates as a motor. This is due to the presence of internal resistance in the windings of the BLDC motor.

Therefore, initial testing was conducted through experimental methods to determine the potential recoverable power for regenerative braking. The experimental setup involved using two coupled motors, each functioning as a driver and a generator. Both motors were individually measured for voltage and current parameters to compare the power consumption and output power of each drive and driven motor.

The controlled parameter in the experiment was the speed of the drive motor. Since the drive and driven motors were coupled on the same shaft, both motors were considered to have the same rotational speed. This BEMF data was utilized for designing the capacity of the DC-DC converter components, as further explained in the subsequent subsection. The experiment resulted in a maximum BEMF of 68V at 3000 RPM of motor rotation and 11 A of generated current, which were used as limitations for the proposed system.

2.3. Supercapacitor bank calculation

Considering the safety factor, the maximum velocity and load were used, which were 70 km/h, or equal to 19.44 m/s, and a maximum load of 2 riders with an assumed weight of 70 kg. With the E-Trail measured weight of 104 kg. Assuming no losses during the conversion process from kinetic braking energy to storage in the supercapacitor, the required supercapacitor capacity can be calculated using Equation 1, which resulted in 46,1 kJ of potential kinetic energy.

Table 1. EV Prototype E-Trail BANGKITS specification

Parameters	Value
Electric Motor	BLDC; 5 kW; 6000 RPM max rotation; Mid-drive; 72V operating voltage; hall sensor-operated
Battery	Li-po cells; 72V 52 Ah ~2.9 kWh; 1C max. cont. charge current; 3C max. cont. discharge current
Motor Controller	72V operating voltage; 150A max. current draw; for hall sensor-equipped motor
Vehicle weight	104 kg
Max velocity	70 km/h
Transmission type	Direct chain drive, 1:5 final drive ratio

Table 2. Specification for GreenCap^{TM} EDLC 500F 2,7 V

Parameters	Value
Capacity	500 Farad
Max. voltage	2,7 Volt
Max. Peak Current	264,7 Ampere
Max. Continuous Current	40 Ampere
Specific Energy	5,69 Wh/kg
ESR (DC)	3,1 mΩ

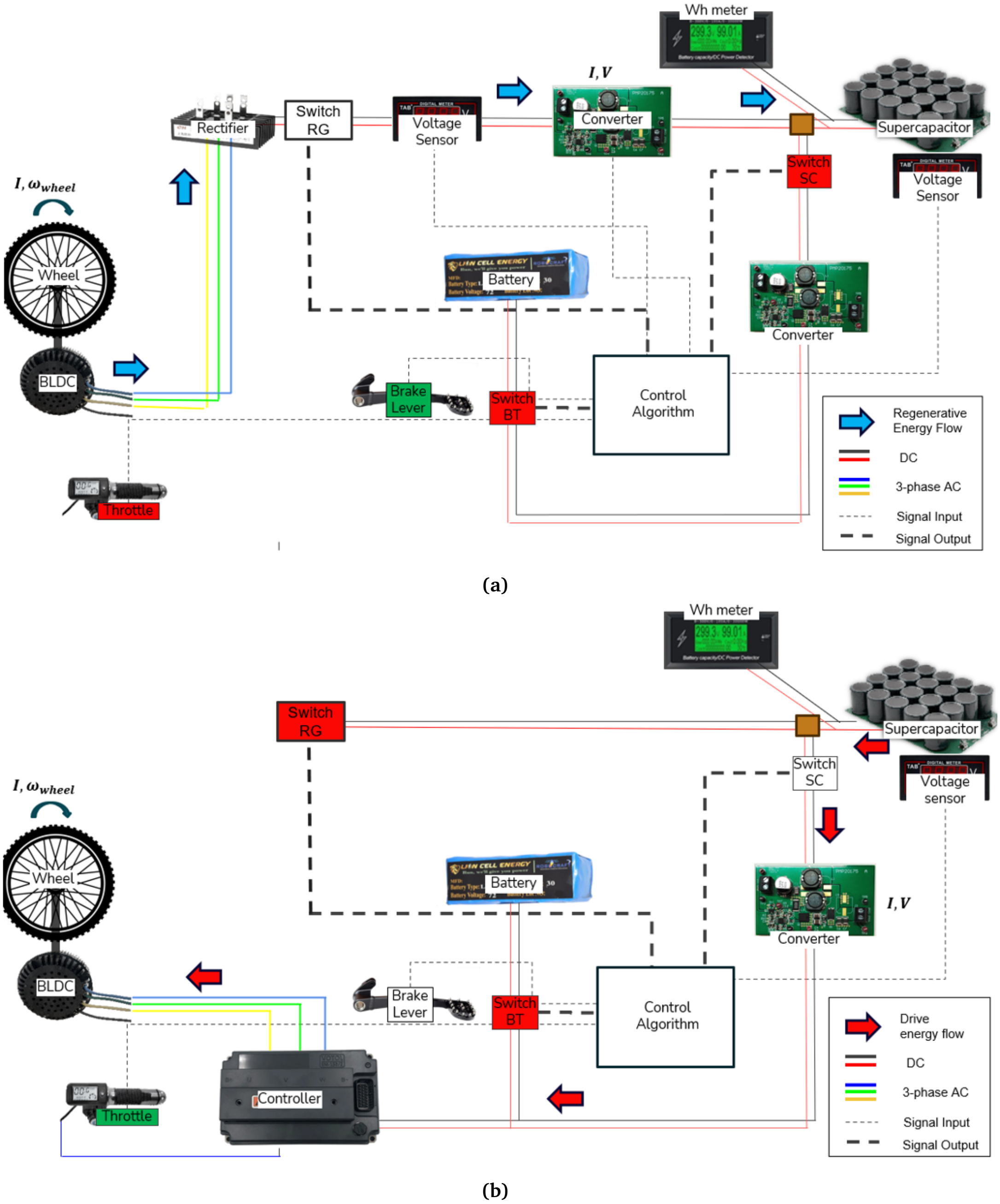


Figure 1. Component working diagram for the proposed regenerative braking system in (a) regenerative mode, and (b) drive mode

Based on the available types of supercapacitors in the market, GreenCapTM EDLC supercapacitors were used. The complete specifications of the supercapacitor can be seen in Table 2.

Therefore, the supercapacitor pack total capacity, nominal voltage, and capacitor total energy results can be obtained using Equation 2, 3, and 4.

$$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + ... \frac{1}{C_2}4 = \frac{24}{500}F = 20,833F \quad (2)$$

$$V_{total} = V_1 + V_2 + ...V_{24} = 24ů2,7V = 64.8V \quad (3)$$

$$E_{cap} = \frac{1}{2} C_{total} V_{total}^2 = 43,74kJ \quad (4)$$

where V and C respectively stand for supercapacitor voltage and capacity.

Since each set of 6 supercapacitor cells was assembled into one module equipped with a voltage balancing circuit, and considering a 100% regenerative efficiency is unattainable, the series arrangement of 24 supercapacitors with a total energy storage capacity of 43.74 kJ is deemed sufficient for use in the E-Trail electric motorcycle. Additionally, the dimensions of the supercapacitor bank arrangement are of special concern to ensure it can fit within the E-Trail electric motorcycle.

The supercapacitor bank is structured in series with 4 modules of supercapacitors. The completed supercapacitor bank also includes a 150 A fuse to protect the circuit in the event of a short circuit.

2.4. System components schematic

The results of the regenerative potential experiment are utilized to design the capacity of regenerative braking components. Thus, based on said experiments, while also comparing it to previously proposed systems from studied references, a component working diagram of regenerative braking is created, as shown in Figure 1 below.

The system operates in two modes: regenerative and drive. In regenerative mode, motor BEMF current charges the supercapacitor through the regenerative circuit. In drive mode, the RG switch disconnects the regenerative system from the drive circuit, including the controller, motor, and battery.

During regenerative braking, the system utilizes the three-phase AC BEMF from the BLDC motor. This voltage undergoes rectification and conversion to enable electric current flow into and storage in the supercapacitor.

In drive mode, the controller regulates current intake from the Hybrid Energy Storage System (HESS) - supercapacitor and battery - based on the supercapacitor's State of Charge (SoC). SoC was indicated as a percentage, with 100% representing a fully charged supercapacitor and 0% indicating depletion. The supercapacitor pack circuit had a maximum voltage set at 60V (100% SoC). Assuming a linear discharge curve for the supercapacitor [9], within an operating range of $10V \leq V_{sc} \leq 60V$, voltage-based SoC estimation can be calculated using Equation 5 below.

$$SoC_{SC} = \frac{V_{current}}{V_{(100\%)}} \times 100\% \quad (5)$$

3. Results and Discussion

3.1. System performance and efficiency test

The testing and performance evaluation of the regenerative braking system based on HESS for the E-Trail electric motorcycle encompasses two distinct stages: regenerative mode testing and drive mode testing.

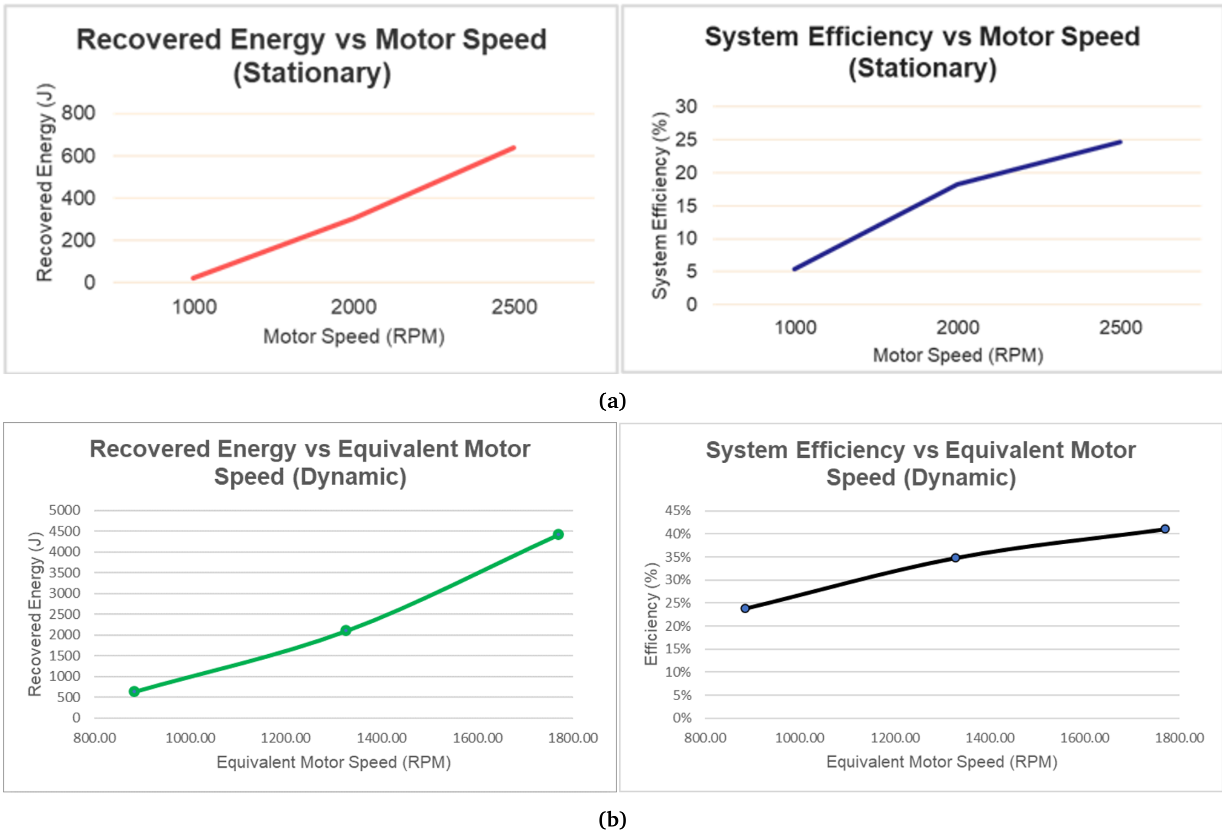


Figure 2. Results for (a) stationary and (b) dynamic tests

A. Regenerative mode tests

A stationary test was conducted using the E-Trail prototype stationed on a paddock stand, to keep the wheel spinning freely, and unloaded. In such conditions, the motor was accelerated to various RPMs, and afterward, the regenerative braking system was activated.

The stationary tests were conducted using 3 RPM variations, 1000 RPM, 2000 RPM, and 3000 RPM. The source of energy for regenerative braking in this test was the rotation of the E-Trail rear tire. Therefore, the rear tire kinetic energy must be calculated beforehand using Equation 6.

$$E_{ktyre} = \frac{1}{2} I \omega^2 \tag{6}$$

Where I refers to the tyre inertia in kg/m^2, and ω is tyre rotation speed in rad/s.

Another significant parameter is the amount of energy stored within the supercapacitor after regenerative system activation. The amount of energy stored/discharged from the supercapacitor after regenerative system activation/discharge can be calculated using Equation 7.

$$E_{SC} = \frac{1}{2} C (V_t^2 - V_0^2) \tag{7}$$

where C is supercapacitor capacitance, V_t and V_0 refer to initial and final voltage value after charge/discharge.

To better compare the results of dynamic and stationary tests, equivalent motor speed in RPM was calculated using Equation 8 as follows.

$$\omega_x = \frac{v_0}{2\pi r} \times 60 \times 5 \tag{8}$$

where vo is velocity in m/s, and r is wheel radius in m.

After acquiring kinetic and supercapacitor charge energy parameters, the regenerative energy recovery efficiency can be determined using Equation 9. Energy recovery efficiency ultimately can determine how well the proposed regenerative braking system performs as an energy-saving device.

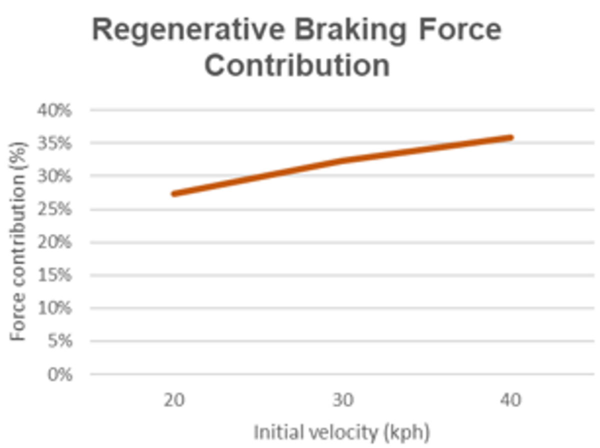
$$\eta_{system} = \frac{E_{regen}}{E_k} \tag{9}$$

where η_{system}, E_{regen}, and E_k respectively stand for system efficiency, recovered regenerative energy, and initial vehicle kinetic energy.

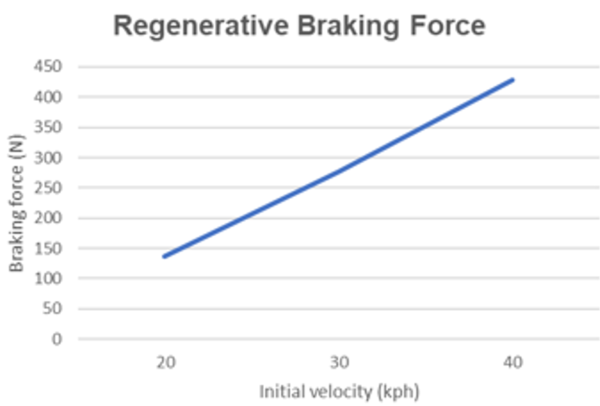
Dynamic on-road tests measured the same parameters as the stationary test. The difference is that while stationary tests used motor speed as the control variable, dynamic tests used vehicle velocity, which was further calculated into equivalent motor speed, for comparison purposes. Velocity served as a more realistic parameter to use in an on-road testing scenario. Consequently, since velocity was used instead of rotation speed, the kinetic energy calculation used the linear formula as shown in Equation 1, but instead of using maximum load and velocity, the parameters used actual properties which were rider mass (70 kg) and velocity variations. While E-Trail prototype weight can be seen in the vehicle specification in Table 1 in the previous section.

The results of static and dynamic regenerative mode tests can be observed in the following Figure 2. At the motor speed of 3000 RPM, an unexpected significant voltage spike (up to 94V) damaged the converter, rendering the data unattainable. The motor RPM can also be converted to the rear wheel rotation speed, which can further be converted to a vehicle speed of approximately 45 km/h.

In summary, the regenerative system effectively recovers kinetic energy during braking, displaying ascending linear trends. Optimal regenerative energy requires an appropriate motor speed for efficient utilization of the generated regenerative voltage [10].

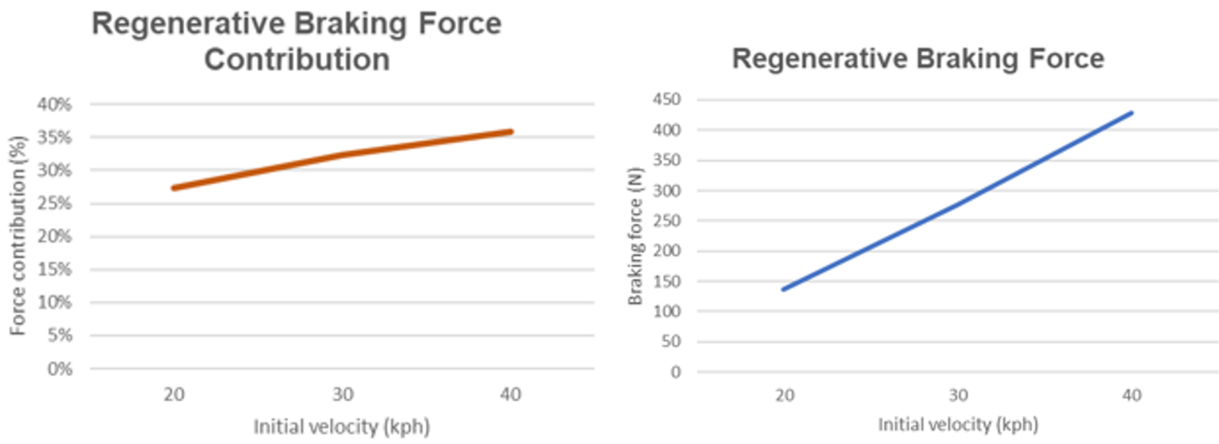


(a)



(b)

Figure 3. Supercapacitor discharge profile in (a) stationary test, (b) dynamic test.



(a) (b)

Figure 4. The results of braking performance test in terms of (a) braking force contribution, (b) braking force vs initial velocity.

Voltage conversion is crucial for ensuring stability in supercapacitor charging, dependent on the converter's performance. Dynamic tests exhibited higher energy recovery and improved efficiency compared to stationary tests, which was likely attributed to the higher kinetic energy involved in dynamic testing. This increased energy recovery efficiency can significantly benefit vehicle operation [11].

B. Drive mode tests

Power draw was calculated using Equation (10) as follows.

$$P_{draw} = \frac{E_{draw}}{t_d} \tag{10}$$

Where E_{draw} is the energy drawn from the capacitor which can be calculated using previous Equation 11, and td¬ is discharge time. The stationary and dynamic tests were conducted using motor speed and velocity variations respectively. The results of tests can be observed in the following Figure 3.

Overall, the system was considered capable of being operated whether in stationary, or dynamic on-road conditions. Tests with higher speed variations were conducted, but the data were annulled due to a damaged converter.

As seen in Figure 3, the supercapacitor has a relatively linear discharge profile, which is in accordance with previously studied references [9]. From Figure 3, it can also be seen that the lowest voltage of the supercapacitor only reached around 22V, and the total energy consumption is just about half of the energy capacity of the supercapacitor as calculated in Equation 4, which was considered a loss of energy. This is due to the converter's limited capability to convert electrical current to a usable range of voltage [3, 10], which is why, further research for DC-DC converter used especially in regenerative braking is highly recommended.

3.2. Vehicle performance tests

Vehicle performance tests were essentially used to test how the HESS-based regenerative braking system affects E-Trail BANGKITS prototype operation performance in terms of braking capability, and driving range. Therefore, the vehicle performance tests were divided into two tests, which are the braking performance test and the on-road driving range test.

A. Braking performance test

Braking force can be calculated using the energy equation between kinetic energy, and the work that is done by braking force along a certain stopping distance, which can be formulated in Equation 11 as follows.

$$\begin{gathered} E_k = W \\ \frac{1}{2}mv^2 = F.S \end{gathered} \tag{11}$$

where W is work, which in turn makes F in this context braking force, and S is distance, or specifically, stopping distance. Braking contribution is an important factor in determining the usability of the system. Braking contribution is stated in percentage, which can be calculated using Equation 12 as follows.

$$\%F_{reg} = \frac{F_{reg}}{F_{total}} \times 100\% = \frac{F_{reg}}{F_{reg} + F_m} \times 100\% \tag{12}$$

where F_{reg} is regenerative braking force, F_m is mechanical braking force, and F_{total} is the total braking force of the vehicle. The test was performed by accelerating the vehicle to a variation of velocity, maintain it, and then hit the brake. Resulting braking distance was then measured each time.

The results of the test can be observed in the following Figure 4.

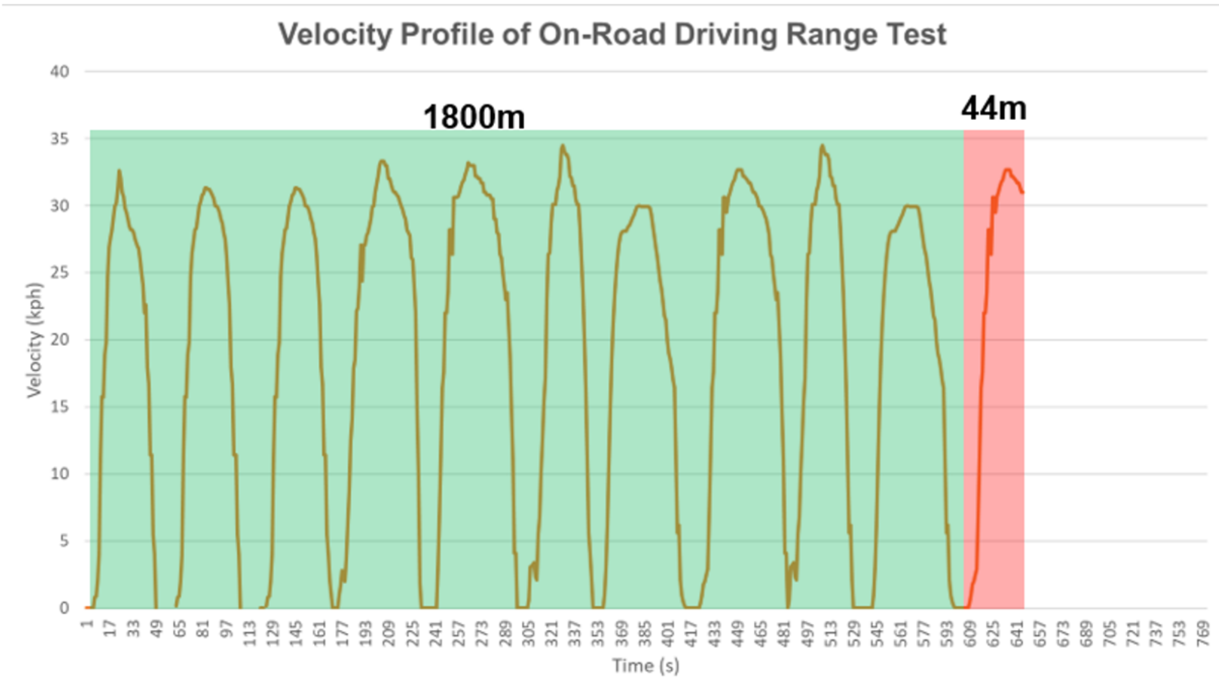


Figure 5. On-road driving range test results in velocity profile

From Figure 5, it is evident that the system effectively functions as a braking apparatus. The trends in braking force and braking contribution percentage increase with initial velocity. These trends align with the results from previous regenerative mode tests on the system. This observation is consistent with the findings of a previous reference, which indicated that regenerative braking becomes more efficient and proficient in energy recovery as the BLDC motor speed increases [12].

However, relying solely on electrical braking through regenerative braking cannot entirely substitute traditional mechanical braking, as indicated in Figure 5, where the change in braking force amount is associated with motor speed [10, 13]. This limitation suggests that electrical braking must always be used in conjunction with mechanical braking on a vehicle to avoid inconsistent braking performance during normal on-road riding.

B. On-road driving range test

The vehicle driving characteristics were limited to a maximum speed of 40 kph. The road test followed a predetermined route with locations on the ITS Surabaya campus, with a round-trip distance of 3.6 km. Routes within the campus environment have numerous speed obstacles such as speedbumps and road turns which cause frequent stop-and-go driving. This mode of driving is quite suitable for increasing the rate of regenerative braking, which in turn increases the energy recovery rate [14, 15].

Figure 5 illustrates the test results, displaying the velocity profile of the E-Trail prototype for approximately half of the test duration. The profile indicates instances of regenerative braking performed to charge the supercapacitor before entering drive mode. Two shaded areas, green and red, are highlighted in the figure. The green area represents periods when the vehicle used the battery, employing regenerative braking during descending curves (vehicle deceleration). In contrast, the red area signifies the utilization of the supercapacitor to propel the vehicle up to speed. Assuming a similar velocity profile for the return trip, the regenerative braking system with the supercapacitor contributed to approximately 2.4% of the total trip distance.

The results of the tests showed that the proposed HESS-based regenerative braking system could recover up to 4410 J of energy with 41% efficiency with an ascending trend as motor speed increased, while in drive mode, the system could successfully drive the vehicle at 1430W power draw, and 14.8s of discharge time. In the vehicle performance test, the system was capable of generating a braking force of 427.92N at 36% braking contribution. The system could also extend the driving range of the vehicle by 2.4% of the test route distance.

By comparison, a similar HESS-based regenerative braking system using ANN and PI-based control algorithm proposed by Naseri, F [4] showed quite different results. The aforementioned system was simulated using a WVU driving cycle and was capable of operating at a maximum efficiency of 48%, while also capable of extending the drive range of the simulated EV by about 5 cycles, or around 50% of the initial drive range. Compared to the results of the proposed system in this research, efficiency-wise, also considering that this research used an actual vehicle prototype to perform the tests, the results were deemed favorable and can be used as a reference for further research, particularly on similar HESS-based regenerative braking system on two wheels electric vehicle. On the other hand, the system's capability to extend the driving range of the prototype was deemed quite poor compared to the mentioned system from the reference. After further analysis, this result was caused by the limited system capacity to recover and store regenerative energy, which caused lengthy supercapacitor charging time, and reduced its useability. These results can be used as an evaluation and further development for potential research of similar systems in the future.

4. Conclusion

This study proposed a methodology for designing a regenerative braking system based on the Hybrid Energy Storage System (HESS) for the EV prototype E-Trail BANGKITS. The potential regenerative energy was determined through testing the BLDC motor of the E-Trail. The results indicated the system's capability to recover and reuse energy to propel the prototype, albeit with some limitations. Additionally, the impact on the performance of the E-Trail prototype after retrofitting the HESS-based regenerative braking system was assessed. The findings revealed that the system successfully aided in the braking process and contributed to extending the driving range of the E-Trail BANGKITS prototype.

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