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REGENERATIVE BRAKING SYSTEM (RBS) MOSFET SWITCHING-BASED DRIVE CYCLE FOR AN ELECTRIC MOTORCYCLE

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ABSTRACT: A regenerative braking system is an advanced technology applicable to transportation, particularly electric vehicles. The purpose of incorporating regenerative braking is to recover energy during braking and deceleration, which can be stored in the battery. This paper aims to study the operation of the regenerative braking system based on an urban drive cycle. This study selects the US60 and NEDC drive cycles as inputs to evaluate future powertrain systems and vehicle concepts. The output torque is calculated longitudinally based on the vehicle dynamic equation to determine whether the torque is negative or positive. When the torque is negative, regenerative braking applies, and the state of charge (SoC) of the battery increases. The concept of regenerative braking is that this system uses four MOSFETs as switches. As a result, at the 50% level of SoC, the first regeneration improved performance by 12.22%, whereas the second showed a smaller gain of 5.96%. Similarly, at the 80% level of SoC, the first regeneration yielded a 12.55% increase, while the second achieved only a 6.19% improvement. The rise in SoC for both levels demonstrates that energy can be recovered when implementing regenerative braking. Therefore, the results obtained from the MATLAB simulation will be used for future studies in implementing a regenerative braking control strategy.

ABSTRAK: Sistem brek jana semula adalah teknologi canggih yang digunakan untuk pengangkutan, terutamanya kenderaan elektrik. Tujuan menggabungkan brek jana semula adalah bagi memulihkan tenaga semasa brek dan nyahpecutan, yang boleh disimpan dalam bateri. Kajian ini bertujuan bagi mengkaji operasi sistem brek jana semula berdasarkan kitaran pacuan bandar. Dalam kajian ini, kitaran pemacu US60 dan NEDC dipilih sebagai input bagi menilai sistem *powertrain* dan konsep kenderaan masa hadapan. Tork keluaran dikira berdasarkan persamaan dinamik membujur kenderaan bagi menentukan tork negatif atau positif. Apabila tork negatif, brek jana semula terpakai, dan keadaan cas (SoC) bateri meningkat. Konsep brek sistem jana semula ini menggunakan empat MOSFET sebagai suis. Hasilnya, pada tahap 50% SoC, penjanaan semula pertama meningkatkan prestasi sebanyak 12.22%, manakala tahap kedua menunjukkan kenaikan lebih kecil iaitu 5.96%. Begitu juga, pada tahap 80% SoC, penjanaan semula pertama menghasilkan peningkatan 12.55%, manakala yang kedua hanya mencapai peningkatan 6.19%. Peningkatan SoC bagi kedua-dua tahap menunjukkan bahawa tenaga boleh dipulihkan bagi melaksanakan brek jana semula.

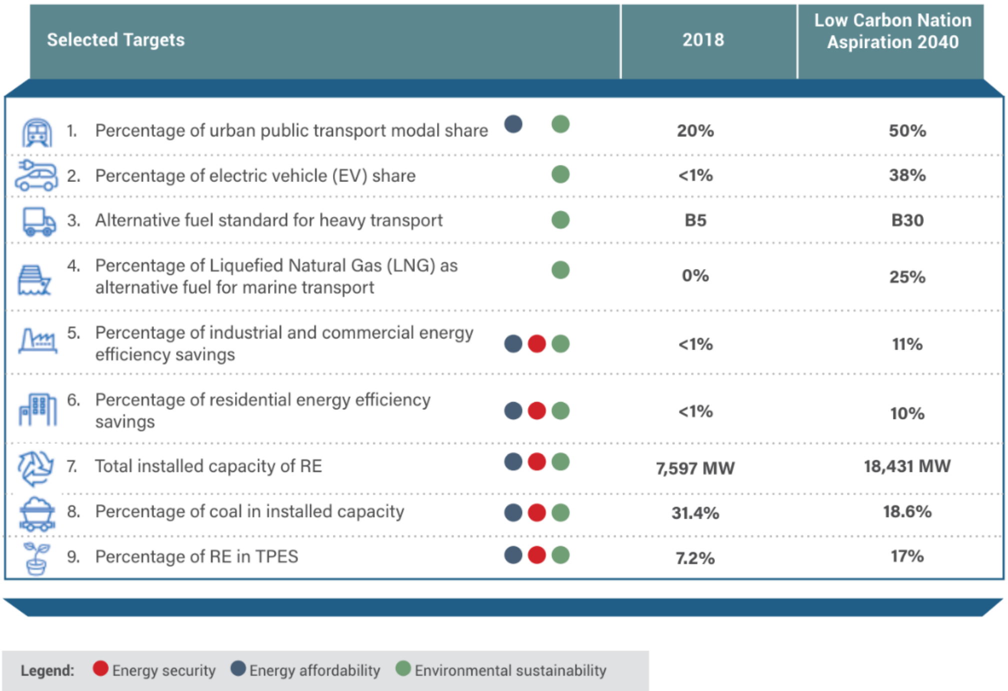
Oleh itu, dapatan kajian yang diperoleh dari simulasi MATLAB akan digunakan untuk kajian masa hadapan dalam melaksanakan strategi kawalan brek jana semula.

KEYWORDS: *Regenerative, Braking, Electric Motorcycle, Drive Cycle, and Recovery Energy.*

1. INTRODUCTION

In this era, technological advancements are paralleled by energy consumption, leading to an energy shortage crisis. This forces researchers to find solutions in new energy generation. In Malaysia, fossil fuels contribute to about 90% of energy production, especially in Peninsular Malaysia, which includes greenhouse gas (GHG) emissions [1]. To address this issue, the Malaysian government has introduced the National Energy Transition Roadmap (NETR) to achieve net-zero carbon emissions by 2050 with renewable energy shares targeting an impressive 40% by 2040 [2]. One significant effort to reduce emissions is the adoption of electric vehicles.

Moreover, Malaysia also aims to reduce GHG emissions through the increased use of renewable energy (RE), as outlined in the 11th Malaysia Plan (2016–2020). This plan continues for the 12th Malaysia (2021–2025), and the main agenda still focuses on low-carbon development, resource efficiency, and the preservation and sustainability of natural resources. However, a major challenge is that industries are the most significant contributors to carbon emissions and environmental impacts. Nevertheless, the government is also committed to the Paris Agreement of 2015 and the decarbonization agenda; the energy transition from gasoline cars to electric vehicles is becoming more imminent [3].



Selected Targets	2018	Low Carbon Nation Aspiration 2040
1. Percentage of urban public transport modal share	20%	50%
2. Percentage of electric vehicle (EV) share	<1%	38%
3. Alternative fuel standard for heavy transport	B5	B30
4. Percentage of Liquefied Natural Gas (LNG) as alternative fuel for marine transport	0%	25%
5. Percentage of industrial and commercial energy efficiency savings	<1%	11%
6. Percentage of residential energy efficiency savings	<1%	10%
7. Total installed capacity of RE	7,597 MW	18,431 MW
8. Percentage of coal in installed capacity	31.4%	18.6%
9. Percentage of RE in TPES	7.2%	17%

Figure 1. Selected targets on Low Carbon Nation Aspiration 2040 compared to 2018 [3].

Through the National Energy Policy 2021– 2024 (NEP 2040), the Minister of Environment and Water (KASA) introduced several strategies to take advantage of the energy sector for socio-economic development, including the Low Carbon Nation Aspiration 2024 [4]. As illustrated in Figure 1, the percentage of electric car use will increase from less than 1% to 38% of the total industry volume (TIV) by 2040. This demonstrates the government's commitment to reducing carbon emissions by building 10,000 charging facilities, comprising 9,000 alternating current (AC) units and 1,000 direct current (DC) units, by 2050.

In Malaysia, the use of electric motorcycles has been increasing since the government announced a rebate of up to RM2,400 in Budget 2024. This incentive scheme encourages electric motorcycle adoption among individuals earning less than RM120,000 annually or less than RM10,000 monthly [5]. However, some modern electric motorcycles still have certain flaws, such as high purchase costs, 'range anxiety' among riders, and a lack of charging stations. The main issue behind these problems is the battery. To overcome this issue, regenerative braking technology can recover and store energy in the energy storage pack.

This paper is divided into five sections. The first section discusses Malaysia's energy policy. Section 2 covers related literature reviews on regenerative braking systems. Section 3 describes the methodology and concept of electric motorcycles, introducing the mathematical equation for the longitudinal direction. Section 4 presents the findings and discussion. Finally, Section 5 provides the conclusion, summarizing the findings and offering recommendations for future work.

2. LITERATURE REVIEW

Electric motorcycles fall under the category of electric vehicles, which are particularly useful in urban areas for riders to move efficiently from one place to another, especially during congested city driving conditions. Electric motorcycles' size is sleeker than other electric vehicles, allowing users to navigate traffic congestion more easily. An electric motor drives battery-powered electric motorcycles. Additionally, the electric drive and control system are key components connected to the motor drive, power supply, and speed control of the motor [6]. Unlike traditional motorcycles that propel themselves using internal combustion engines (ICEs), electric motorcycles are distinguished by their electric devices, control systems, and mechanical systems, such as power drives.

The power supply from the battery sent to the drive motor converts electrical energy into mechanical energy through a transmission system or by directly driving the wheel. Lead-acid batteries are the most widely used power source in electric vehicles [7]. However, due to their lower specific energy, slower charging speed, and shorter lifespan, they are gradually being replaced by other types of batteries, such as lithium-ion, as electric vehicle technology advances [8]. Meanwhile, the driving device generates torque, which are translated and converted into ground forces through the wheel, propelling the electric motorcycle forward.

Brakes are another critical vehicle component, responsible for slowing down and stopping the vehicle. In electric motorcycles, most braking systems are electromagnetic, which can control the driving motor circuit to generate power. During deceleration and braking, the energy produced can be converted into current to charge the battery, making it reusable [9]. This concept is known as regenerative braking.

2.1. Regenerative Braking System (RBS)

Many motorcyclists use their motorcycles for long journeys, leading to concerns about battery capacity and frequent recharging to maintain the battery's state of charge (SoC) until they reach their destination [10]. However, modifying an electric motorcycle to increase battery capacity is challenging, costly, and cumbersome. Finding a solution to this problem is crucial, as electric motorcycles have the potential to revolutionize urban commuting by reducing carbon emissions and traffic congestion and providing an efficient alternative to traditional internal combustion engine-powered vehicles [11].

Regenerative braking is a technology designed to extend the travel range of electric vehicles. When the vehicle slows down, kinetic energy is converted into electrical energy, preventing energy wastage [12]. This process utilizes the motorcycle's motion to generate electricity stored in the battery. It assists in slowing down the motorcycle while recharging the battery, enhancing overall energy efficiency. Depending on the vehicle's requirements, the stored energy can be utilized immediately or later [13]. Figure 2 illustrates the energy flows between traditional and electric vehicles. In traditional vehicles, kinetic energy is converted into heat and wasted. However, with regenerative braking in electric vehicles, kinetic energy is captured and stored in a storage device for future use.

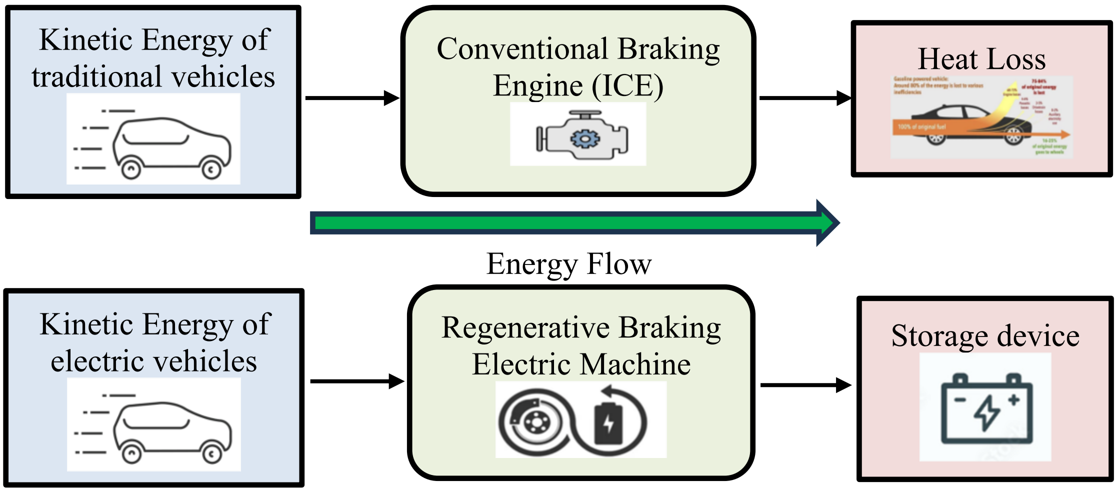


Figure 2. Energy flows for both traditional and electric vehicles.

Moreover, regenerative braking can capture 10% to 30% of kinetic energy, depending on the system. During aggressive braking, the friction brake mainly slows down the motorcycle, with regenerative braking offering additional support. However, under normal braking conditions, the regenerative system can recover up to half of the energy [14]. Advanced regenerative braking systems can recover 70% to 80% of energy using sophisticated control strategies, allowing for more precise and responsive braking. When the brakes are applied quickly, the energy recovery rate is lower than with moderate braking [15].

Regenerative braking is the only technique to recharge the batteries of electric vehicles without requiring any additional connection between the electric motor and the drive wheels. According to Vasiljevic et. al. [16], this type of brake can increase the travel range by up to 30%, depending on the type of vehicle, terrain, temperature, and environment. It allows batteries to recharge during downhill movement and deceleration and further store it in the onboard battery for later use [17]. The advantages of the regenerative braking system include extending the vehicle's range, reducing fuel consumption for hybrid cars, and decreasing maintenance for disc and brake pads of friction brakes [18].

On the other hand, electric vehicles without regenerative braking may not benefit from energy recovery capabilities, but they could offer other advantages. Depending on the vehicle was implemented, these might include simpler system designs, lower maintenance requirements, and reduced overall system complexity [19].

2.2. Regenerative Braking Implementation using MOSFET

Electric motors are propulsive motors and act as generators to recharge the vehicle's battery during braking. Motor controllers can be adjusted to enable regenerative braking. The motor can be modelled as a series circuit consisting of an inductor and a voltage generator. The resistor and inductor represent the resistance and inductance of the motor's electromagnets. The voltage generator signifies the motor's spinning voltage, known as back electromagnetic force (EMF). The back EMF voltage is proportional to the motor's RPM. Figure 3 shows the connection between the inductor and the voltage source.

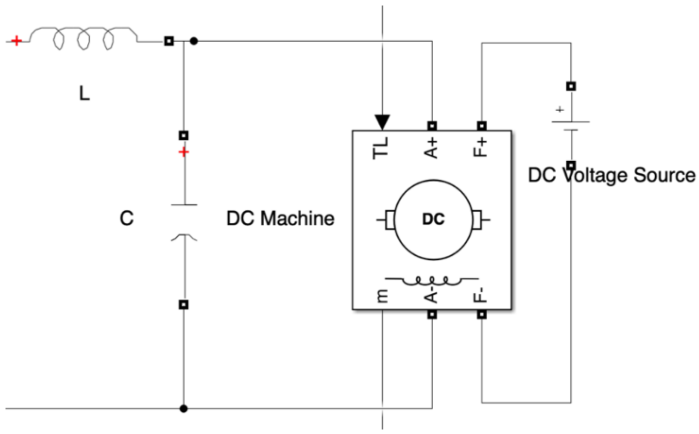


Figure 3. The circuit connection of the inductor and DC motor

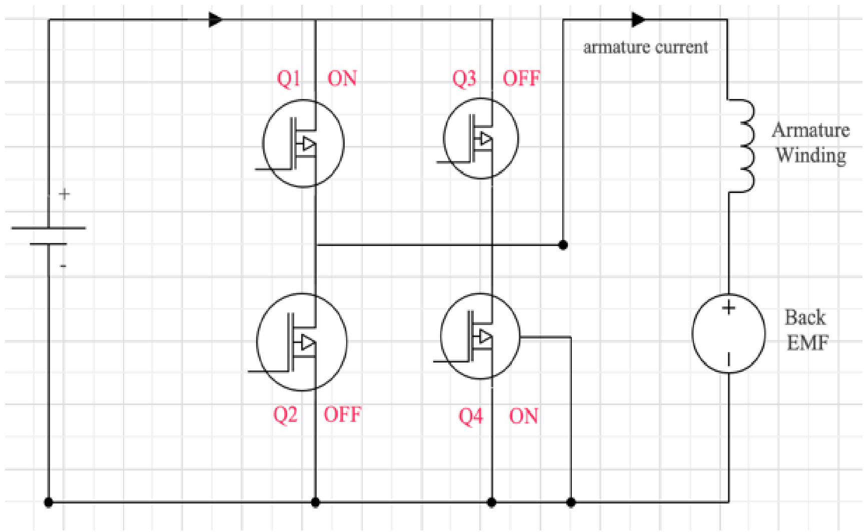
When the motor rotates, it generates the back EMF voltage proportional to its rotational speed. During acceleration, the current decreases, and the motor's speed stabilises the back EMF to produce torque [20]. This torque is enough to overcome friction and the motor's mechanical load. However, if an external force drives the motor, such as the vehicle going downhill, the rotation can cause the back EMF to match battery voltage, and current will flow from the motor to the battery, creating a regenerative braking situation. Equation 1 describes the relationship between back EMF and torque.

$$e_a(t) = \frac{1}{K_t}\left(R_a T_m(t) + L_a \frac{dT_m(t)}{dt}\right) + K_b V_b(t) \tag{1}$$

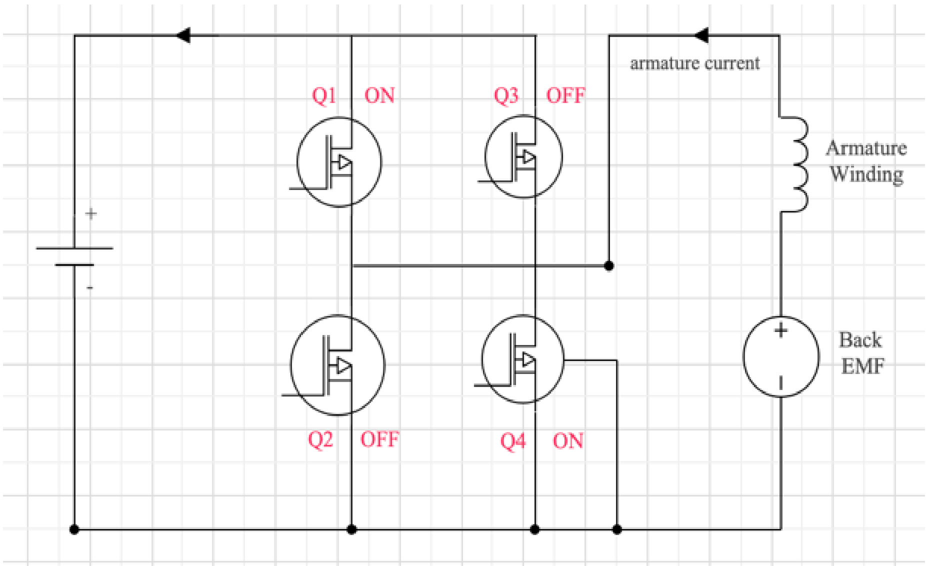
where T_m is the torque developed by the motor, V_b is the back EMF, R_a is the armature resistance, L_a is the armature inductance, K_t is the motor torque constant, and K_b is the back EMF constant.

In regenerative braking systems of electric motorcycles, energy recovery can be achieved using an inverter and a DC machine, such as a brushless DC motor (BLDC) [21], a permanent magnet synchronous DC motor (PMSM) [22], and a DC motor. MOSFETs are widely used in power devices, such as DC–DC and DC–AC converters, due to their ability to switch rapidly between ON and OFF states by applying voltage to the gate. MOSFETs can operate in both motoring and generating modes. Meanwhile, the battery pack is also an essential part of the regenerative braking system, providing power during motoring mode and serving as an energy storage device during regenerative mode [24].

The MOSFET circuit consists of diodes that store energy back into the battery pack by conducting in the forward direction. This circuit is known as an inverter circuit, as it inverts the DC voltage supplied by the battery using a controlled switching sequence of the switches Q1 to Q4. In monitoring mode, a controller and gate driver integrated circuit (IC) drive the motor during the initial state and acceleration. A BLDC motor offers power-saving advantages over other motor drives, high efficiency, and excellent controllability [25]. The circuit diagram operation for the electric motorcycle can be divided into two stages: a) motoring mode and b) regenerative mode, as shown in Figure 4.



(a) Driving mode



(b) Regenerative mode

Figure 4. The equivalent circuit of a BLDC circuit and an inverter

During motoring mode, the high-side switches Q1 and Q4 operate in pulse width modulation (PWM), while the low-side switches Q2 and Q3 operate in standard high/low switching mode. PWM allows for control of the motor's torque, with current flowing from the positive to the negative terminal of the voltage source. Varying voltage can be achieved by turning the power to the motor ON and OFF using MOSFETs arranged in a half-bridge (unidirectional) or full bridge (bidirectional). Combined with the motor's inductance, this switching effectively makes the controller behave like an adjustable voltage source, proportional to the switch's ON/OFF duty cycle; however, in braking energy regeneration for electric motorcycles, the electric machine functions as a generator, inducing a back EMF. This back EMF is usually lower than the battery voltage. The induced back EMF must be boosted to charge the battery using a DC-DC converter. In regenerative mode, every switch from Q1 to Q4 operates in PWM switching mode. Due to the continuous switching of the PWM signal, a distinction must be made between the ON and OFF PWM conditions. Compared to motoring mode, in regenerative braking mode, the current flows from the positive terminal of the back EMF to the negative terminal.

3. METHODOLOGY

Each electric motorcycle has a few main parts, including an electric motor, a chassis, a transmission, and two wheels. The sizes and features of these components depend on the type of motorcycle. There are five categories of motorcycles: standard bikes, cruisers, touring bikes, sport bikes, and dirt bikes. Motorcycles are quite complex machines with many finely tuned mechanical parts. Figure 5 shows the electric motorcycle structure for the regenerative braking system.

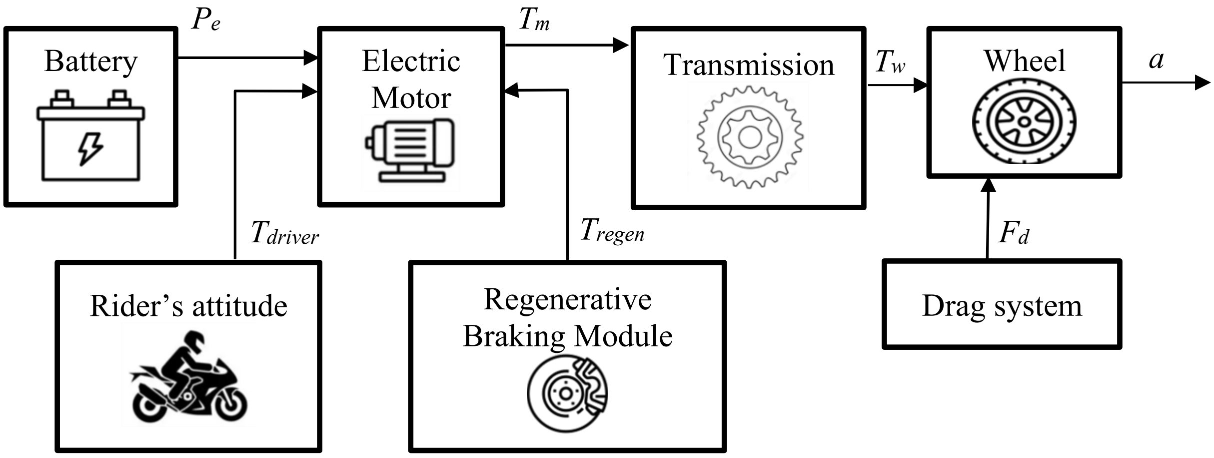


Figure 5. Structure of the motorcycle model.

The electric motorcycle model will capture the longitudinal dynamics, braking forces, energy, and battery state of charge (SoC). The battery simulates the consumed electric power, P_e, to produce the torque on the electric motor, T_m. This motor torque is then used to simulate the single gear in the transmission, considering the gear ratio to generate the wheel torque, T_w. The longitudinal vehicle dynamics help with the vehicle's longitudinal deceleration. The model takes rider input and the regenerative braking module as inputs for the motorcycle model.

3.1. Electric Motorcycle Modeling

The motorcycle is designed to move primarily in one direction, influenced by all the forces acting along this direction. We only consider single-dimensional longitudinal dynamics. Figure 6 shows the force at work on a motorcycle moving up an inclined road at an angle of θ.

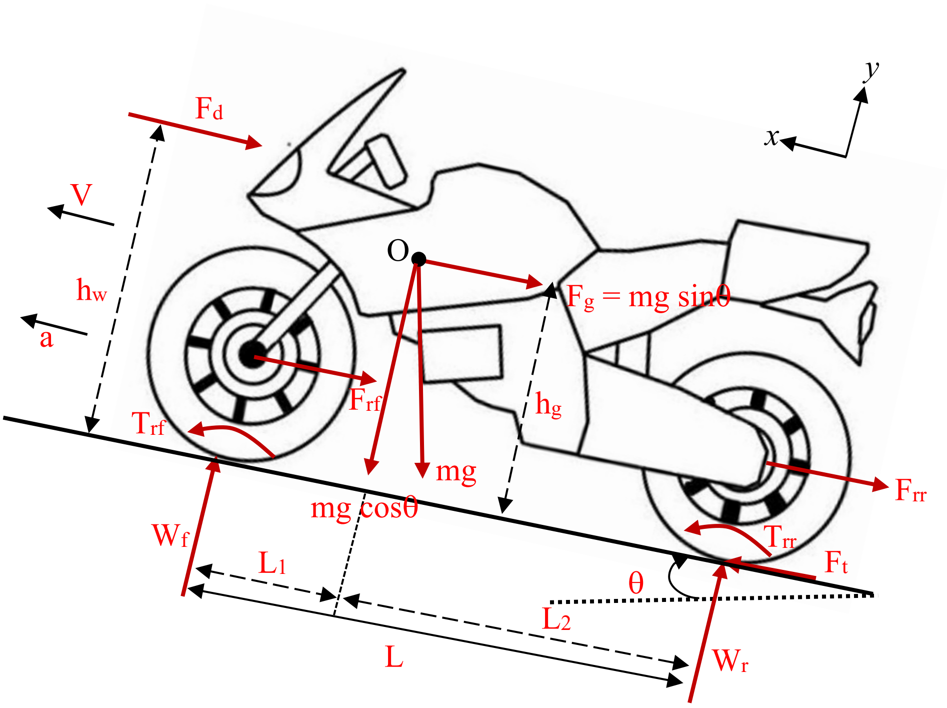


Figure 6. Forces acting on a motorcycle in the longitudinal direction [26].

The traction force, F_t, is created by the friction between the drive wheel's tire and the road surface, propelling the motorcycle forward. This force comes from the engine's torque and is transferred through the transmission to the drive wheel. As the motorcycle moves, it faces resistance from tire rolling, air drag, and gravity, especially when going up or down a hill. According to Newton's second law, acceleration and deceleration can be calculated by finding the difference between the traction force and the sum of these resistance forces.

$$\frac{dV}{dt} = \frac{F_t - \sum F_f}{m} \tag{2}$$

where V is the speed of the motorcycle along the longitudinal x-direction, F_t is the total tractive force, $\sum F_f$ is the total resistance force, m is the motorcycle's total weight.

In the longitudinal direction, the major external forces on a two-axle motorcycle are the rolling resistance of the front and rear tires, the air resistance force, the uphill or downhill resistance force, and the tractive force. Then, the mathematical modeling of motorcycle motion in the longitudinal direction can be expressed by

$$m\frac{d}{dt}V = F_t - (F_{rf} + F_{rr} + F_d + F_g) \tag{3}$$

The first term on the right side is the total traction force, while the second term is the resistance.

$$\left.\begin{aligned} F_r &= mgf_r \cos\theta \\ F_d &= \frac{1}{2}\rho A_f C_d (V - V_w)^2 \\ F_g &= mg \sin\theta \end{aligned}\right\} \tag{4}$$

Equation (4) represents the resistance of the motorcycle, which hinders its motion, encompassing the rolling resistance of the tires, Fr, aerodynamic drag, Fd, and grading resistance, Fg. Moreover, Cd signifies the aerodynamic drag coefficient, which is contingent on the motorcycle's shape, and Vw denotes the wind speed in the motorcycle's direction. The frontal area, A_f is usually 70-90% of the area calculated from the motorcycle's width and height with riders. The aerodynamic drag coefficient, C_d, typically ranges from 0.5 to 0.7 and g represents gravity, which is 9.8 m/s².

3.2. Modeling the Regenerative Braking System

The regenerative braking system considers various factors to recuperate energy and store it in the battery pack. The regenerative braking force produces torque for the system. While ascending, the regenerative force, Fregen, diminishes because of the augmented force, Fload, from the incline. Conversely, the regenerative force escalates while descending as the load force interacts with the downward slope.

$$\left.\begin{aligned} F_{regen} &= F_{br} - F_{fric} \\ F_b &= F_{load} - F_a \\ ma &= F_{br} - F_{load} \end{aligned}\right\} \tag{5}$$

where F_{br} is the motorcycle braking force, F_{load} is the road load force, which includes aerodynamic and rolling resistance, and F_a is the inertial force. However, F_{br} £ 0 is the deceleration force from the deceleration device, and F_{fric} £ 0 is the frictional force from the hydraulic mechanical braking system.

Energy and power are key factors in energy management systems. Therefore, several formula formulations can be used to analyze energy recovery as well as energy consumption for the system.

$$\left.\begin{aligned} E_c &= \frac{E_b}{d} \\ E_b &= E_t + E_{load} + E_{loss} - E_{regen} \\ E_b &= \int_{traction} P_{b_{out}} dt + \int_{regen} P_{b_{in}} dt \\ P_{b_{out}} &= \frac{V}{\eta_m}\left(m\frac{dV}{dt} + mgf_r + \frac{1}{2}\rho C_d A_f V^2\right) \\ P_{b_{in}} &= \frac{\alpha V}{\eta_m}\left(m\frac{dV}{dt} + mgf_r + \frac{1}{2}\rho C_d A_f V^2\right) \end{aligned}\right\} \tag{6}$$

Equation (6) is about energy consumption and energy. Ec is the energy consumed, Eb is the total energy from the battery, and d is the distance travelled. Et is the total energy required to move the motorcycle, Eload is the energy for accessories on the motorcycle, Eloss is the energy lost due to inefficiencies, and Eregen is the energy generated during regenerative braking. So, the net energy consumption is the sum of the power output at the battery terminal and the regenerative braking power, with a negative sign. When the battery energy consumption matches the total energy in the battery, the resistance power, and the effectiveness of regenerative braking. Pbout is the battery power output, and Pbin is the regenerative braking power output with the regenerative braking factor, a, which ranges from 0 to 1. Finally, the total power required for the electric motorcycle can be calculated using equation (7).

$$P_{req} = F_t V \tag{7}$$

3.3. MATLAB Simulation Modeling

In this part, a vehicle dynamic modelling approach is designed using MATLAB/Simulink. The proposed modelling is based on mathematical modelling in the longitudinal direction. The detailed MATLAB/Simulink model of the electric motorcycle is shown in Figure 7. It consists of three primary blocks: forces acting on the motorcycle, power, and energy. The input is the speed from the drive cycle, and the outputs are distance travelled, energy, power, and torque. This simulation allows each functional block to be easily upgraded and improved. Additionally, the model is developed using equations (3-6), which can be solved directly within the model. This simulation aims to understand the concept of electric motorcycles before implementing any control strategies in the regenerative braking system. Meanwhile, Table 1 shows the motorcycle parameters used in the MATLAB simulation based on the retrofitted Honda CBR250RR [10].

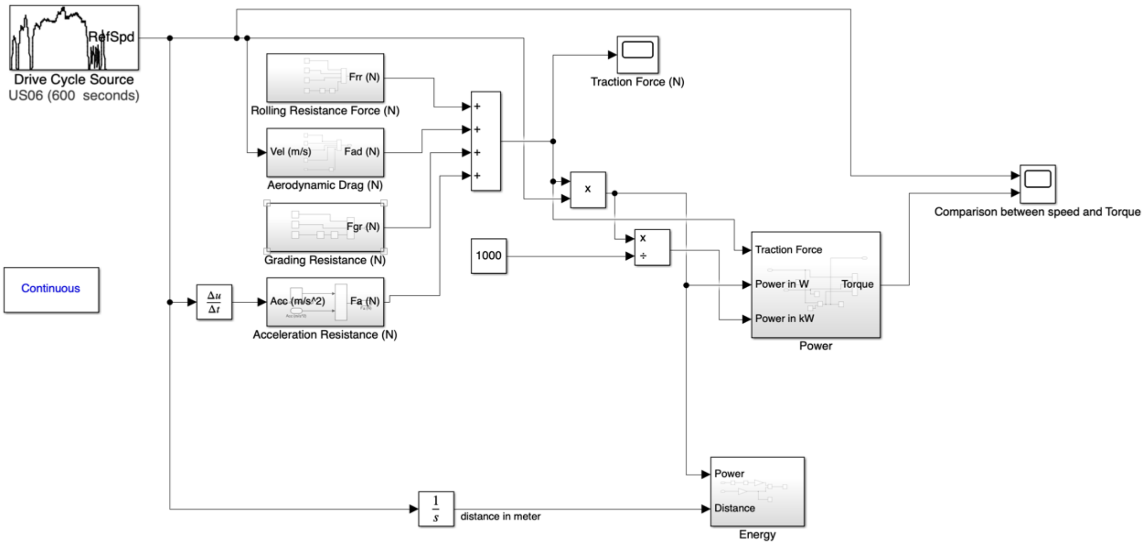


Figure 7. MATLAB/Simulink for electric motorcycle model.

Table 1. Motorcycle dynamic parameters

Parameter	Symbol	Value
Mass of vehicle	M	180 kg
Acceleration due to gravity	G	9.81 m/s^2
Rolling resistance coefficient (on road)	f_r	0.013
Grading angle	θ	0 °
Density of air	ρ	1.202 kg/m^3
Radius of tire	r_w	0.3149 m
Vehicle frontal area	A_f	0.6 m^2
Aerodynamic drag coefficient	C_d	0.7
Gear ratio	GR	0.192054

Figure 8 shows the model for the regenerative braking system using four MOSFETs and a DC machine. The load torque input is applied to the motor in this MATLAB simulation. The model includes a 50 HP, 240 V, 1750 RPM machine with a series inductor and capacitor, connected to a lithium-ion battery. For a battery, it will represent the voltage, current, and state of charge (SoC). The MOSFETs act as the switch. When S1 and S4 are ON, the electric motorcycle can either move forward or brake, depending on acceleration and deceleration. During deceleration, the torque becomes negative, indicating regenerative braking, increasing the battery's charge state. The battery's state of charge will start to increase if it is at 80% or below.

The input torque, TL, is the torque applied to the shaft. The flow of the armature determines the motor's mode. The electromechanical torque, T_e, is proportional to the armature current, I_a.

$$T_e = K_T I_a \tag{8}$$

K_T is the torque constant. The motor operates in motor mode if the input torque, TL, is greater than 0 (TL > 0). The system operates in generator mode if TL is less than 0 (TL < 0).

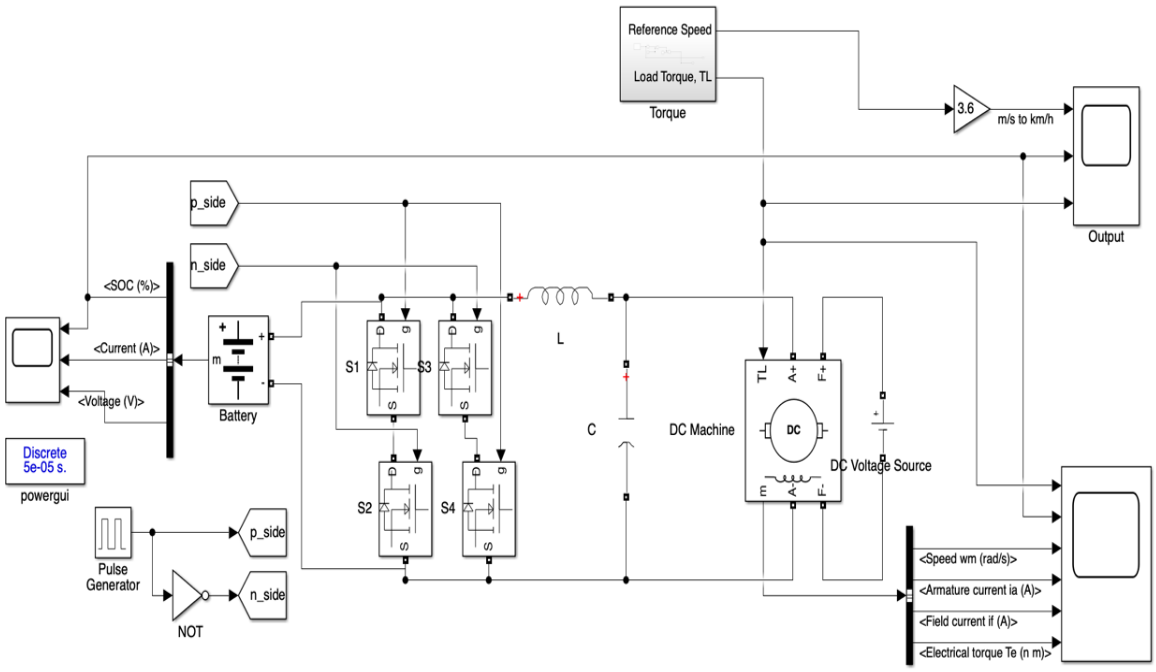


Figure 8. MATLAB/Simulink for regenerative braking of the electric motorcycle model.

In the MATLAB simulation, the four MOSFET switches (S1–S4) operate in pulse width modulation (PWM) mode. Pulse width modulation (PWM) is used as the switching mode to control the torque developed by the motor. The PWM signal continuously switches the MOSFETs ON and OFF, distinguishing between the ON and OFF PWM conditions. When the switching mode is changed to the energy-regenerative mode, a braking signal from the rider is sent to the controller. The PMW switching mode continuously switches the switches ON and OFF. In the ON PWM condition, switches S1 and S4 are turned ON, supplying voltage from the battery to energize winding L. To achieve this, switches S2 and S3 are turned OFF, changing to the OFF PWM condition, thereby supplying energy back to the battery.

4. SIMULATION RESULTS AND DISCUSSIONS

This paper aims to study and implement the regenerative braking system that recovers energy wasted during braking and stores it back in the battery for further driving. The new model of regenerative braking in the electric motorcycle is presented in a MATLAB simulation. This study considers two drive cycles: US60 and NEDC. The drive cycles are represented by graphs that plot vehicle speed against time. They are used to evaluate the performance of the motor, transmission, and emissions control system. The US60 drive cycle represents aggressive, high-speed, and/or high-acceleration driving behavior, rapid speed fluctuations, and driving behavior following startup. Meanwhile, the NEDC drive cycle, known as the New European Driving Cycle, represents the typical European car usage. It consists of four repeated urban driving cycles lasting until 800 s and an extra-urban driving cycle.

Figure 9 shows the drive cycle of US60 and the torque graph obtained from the motorcycle modelling. From the figure, the US60 drive cycle features high speed and quick acceleration, covering it in 10 minutes. It averages 77 km/h and reaches a top speed of 130 km/h, with four stops included. The cycle represents a 12.8 km route with an average speed of 78 km/h, with a duration of 596 seconds. For the torque, negative torque occurs when the speed is decreasing in the last 10 minutes. This negative torque helps determine the regenerative braking system.

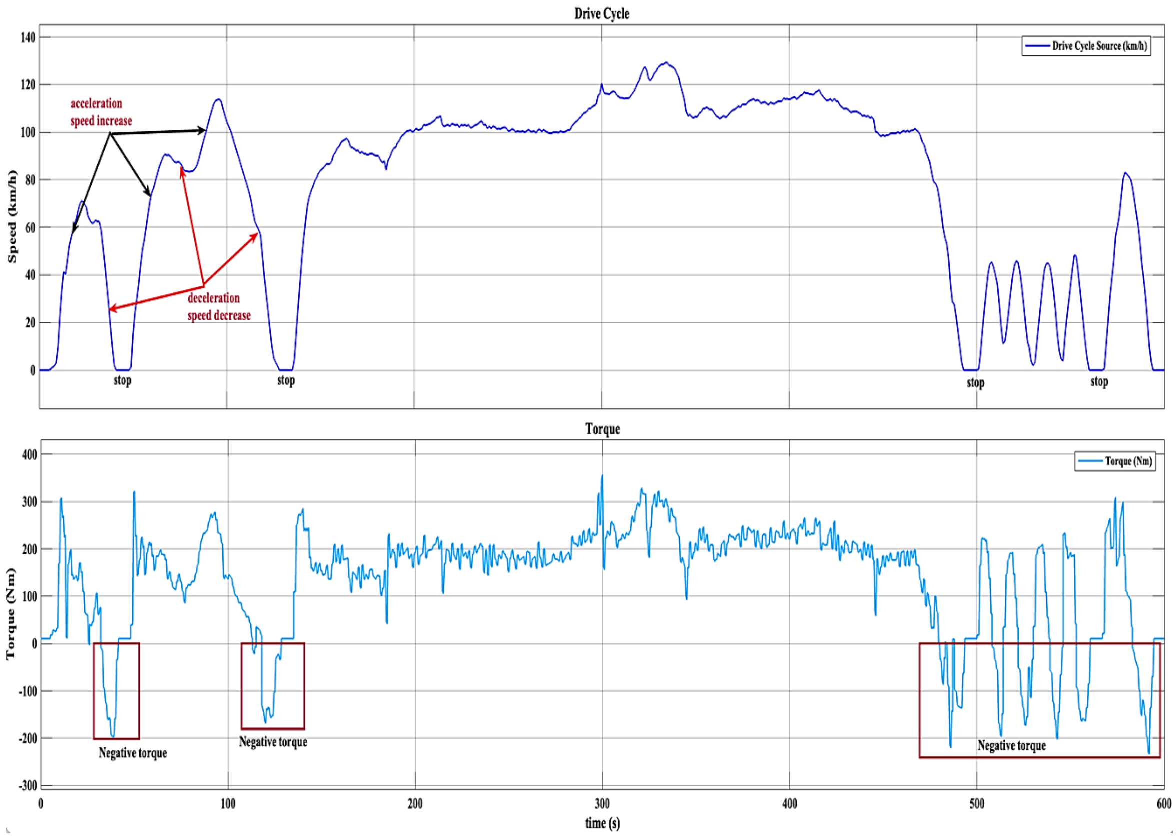


Figure 9. US60 drive cycle and produced torque.

Figure 10 shows the NEDC drive cycle in kilometers per hour for the first graph, while the second graph illustrates the torque over 1180 seconds. These graphs are generated using the vehicle modeling equation. The complete NEDC consists of four repeated urban cycles followed by an extra-urban cycle to simulate highway driving, reaching a maximum 120 km/h speed. This cycle is commonly used for testing electric motorcycle energy consumption and regenerative braking performance testing. The speed pattern for the extra-urban cycle fluctuates and increases until it reaches 120 km/h, then decreases. The negative torque for the extra-urban cycle occurs only once before the motorcycle stops, allowing maximum energy recovery optimization in this phase.

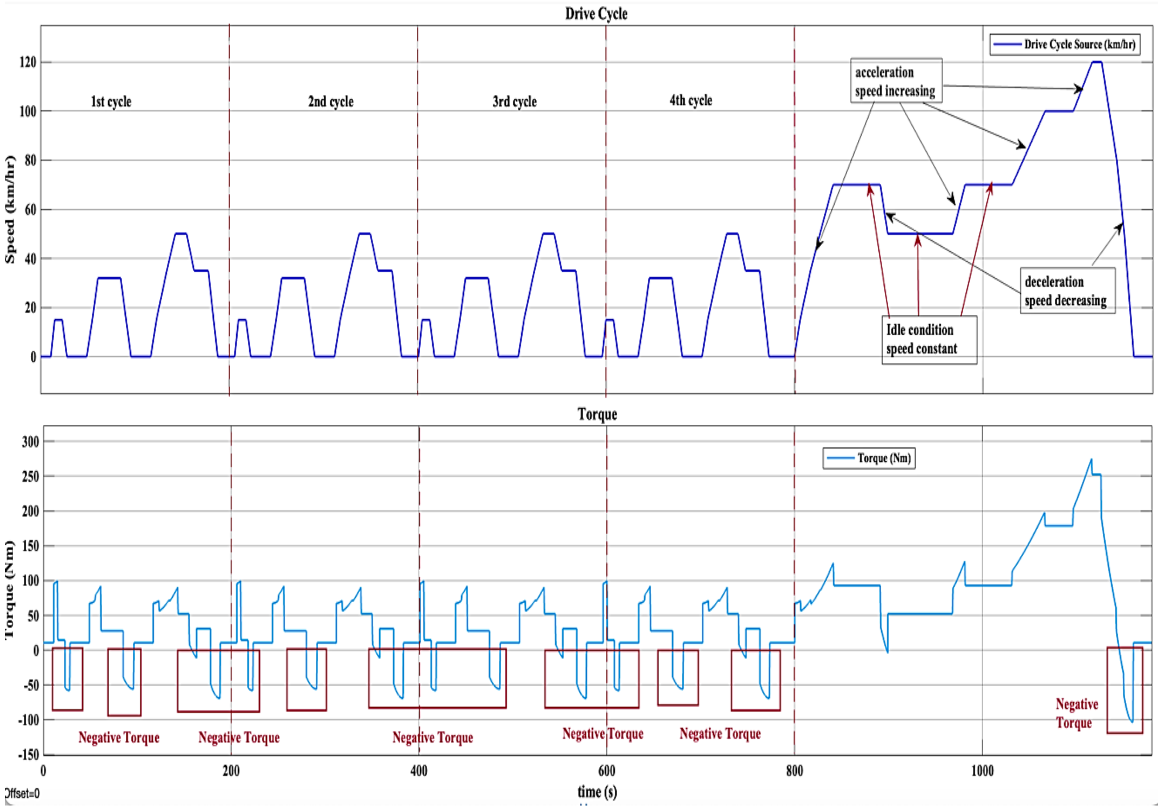
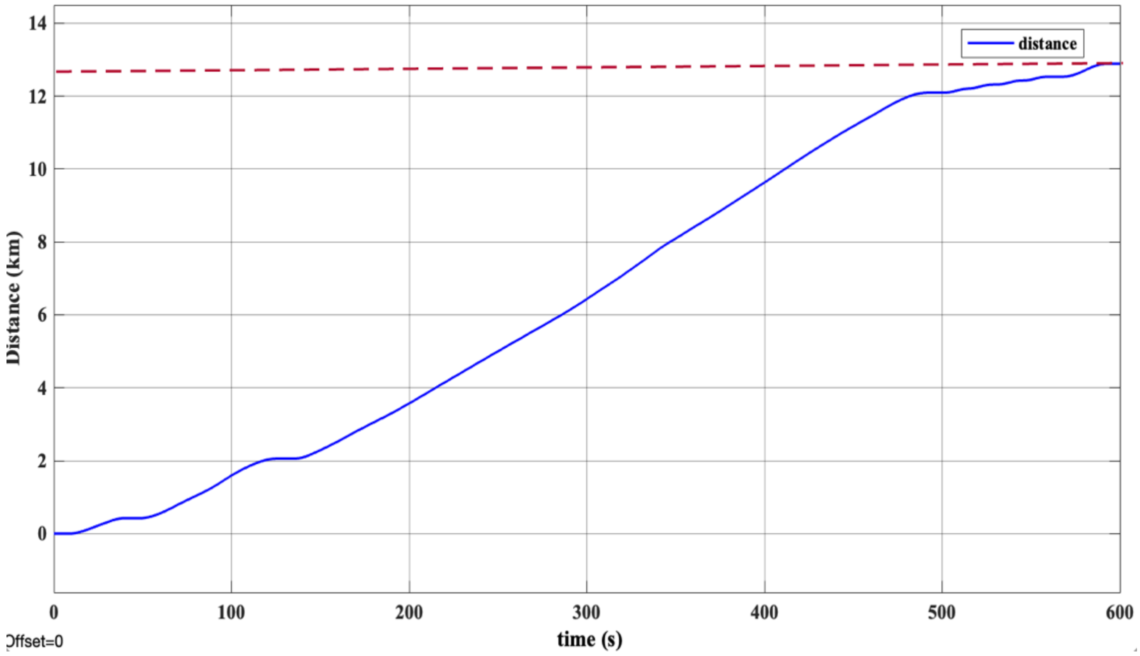
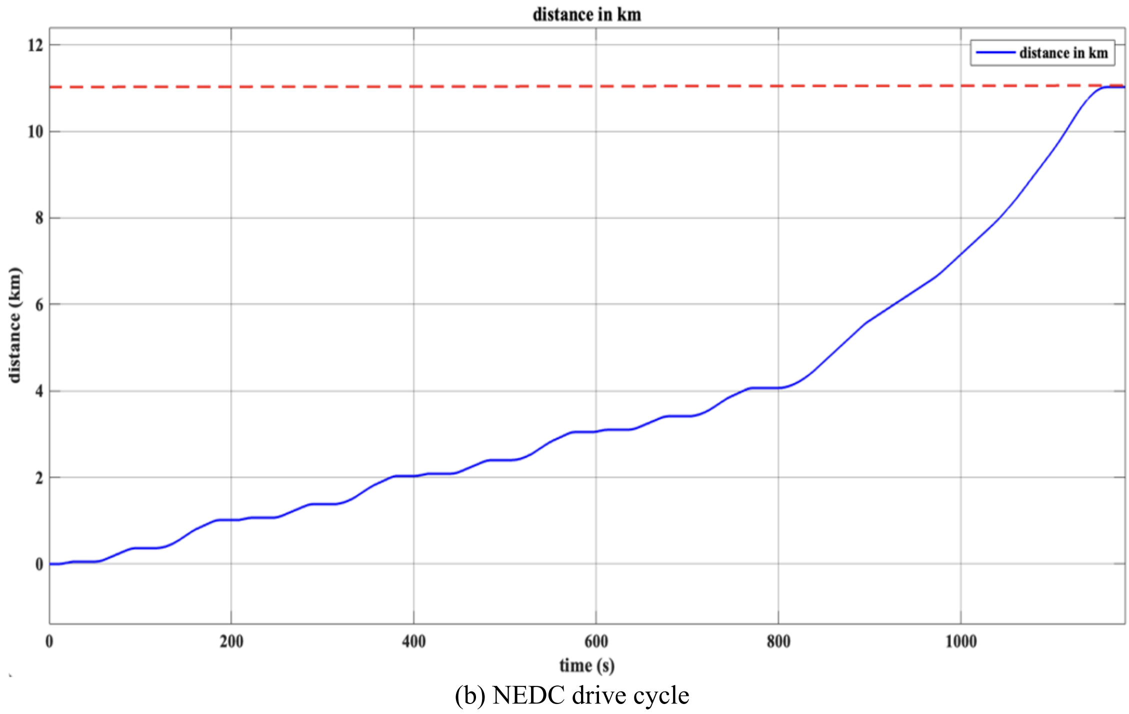


Figure 10. NEDC drive cycle and produced torque.

In the MATLAB simulation, the energy consumed can be estimated by integrating the total power and dividing it by the total distance covered by the electric motorcycle in kilometers. The total distance for the US60 drive cycle in 600 seconds is approximately 13 km, while for the NEDC drive cycle in 1180 seconds, the distance travelled is 11 km, as shown in Figure 11. Meanwhile, Figure 12 illustrates the power consumption for the US60 and NEDC drive cycles. The total power consumed for both cycles is 120 Wh/km and 61 Wh/km, respectively. Once energy consumption is determined, the energy recovery through regenerative braking can be calculated.

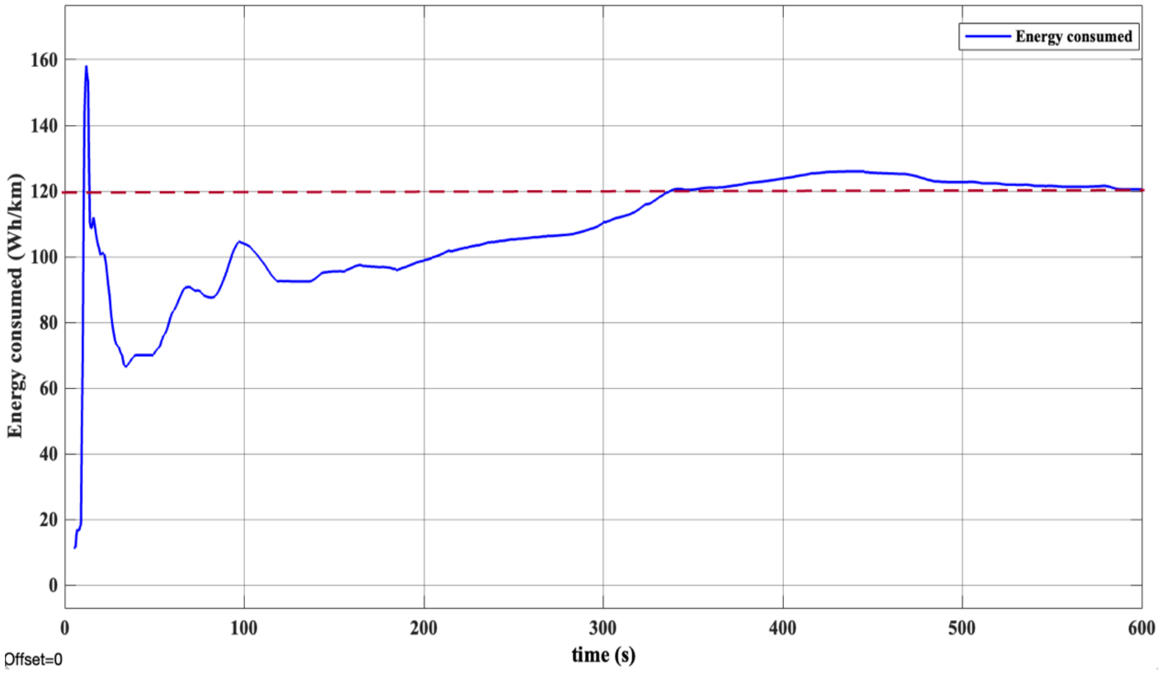


(a) US60 drive cycle

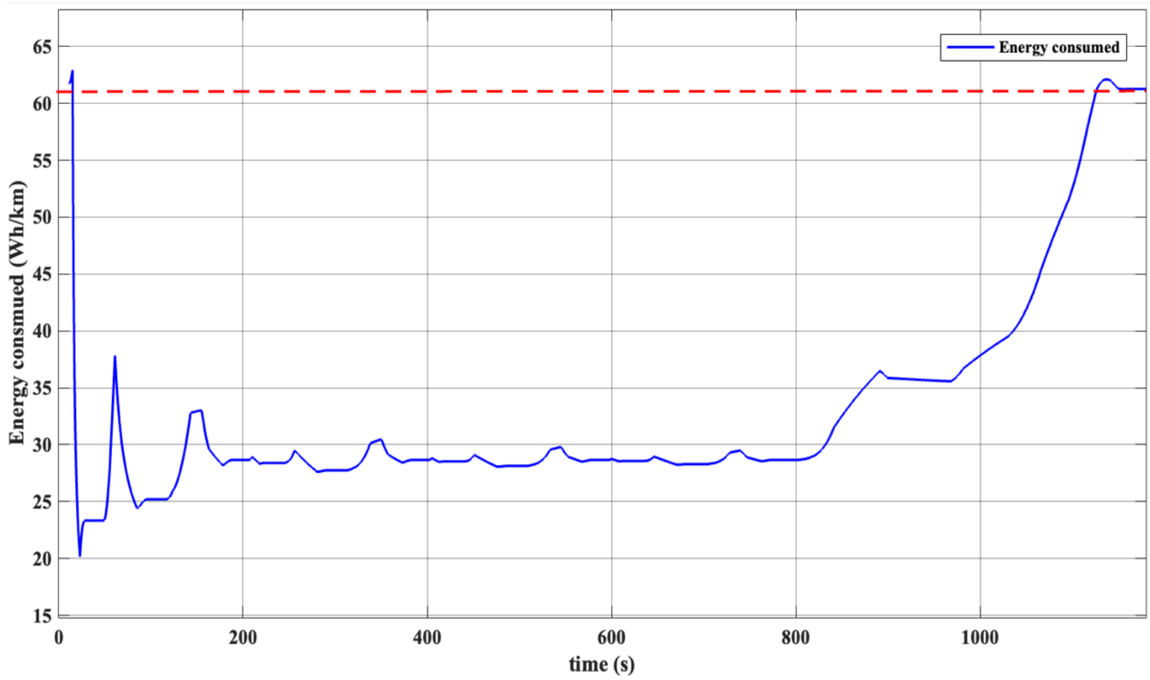


(b) NEDC drive cycle

Figure 11. Total distance for US60 and NEDC drive cycles.



(a) US60 drive cycle



(b) NEDC drive cycle

Figure 12. Total energy consumed for US60 and NEDC drive cycles.

The concept of a regenerative braking system is studied in the second implementation using MATLAB simulation. As mentioned earlier, negative torque indicates the occurrence of regenerative braking. During regenerative braking, the state of charge (SoC) of the battery increases, essentially recharging the battery. This recharging occurs when negative torque is applied, causing the battery to charge as the speed decreases. In this study, the concept of regenerative braking is applied specifically to the US60 cycle. Two SoC levels, 80% and 50%, are chosen to evaluate the effectiveness of braking within the system. In this system, the input torque, TL, is provided by a lithium-ion battery and four MOSFETs connected to a DC

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machine. Figure 13 displays the speed graphs based on the drive cycle, input torque, and state of charge over 250 seconds.

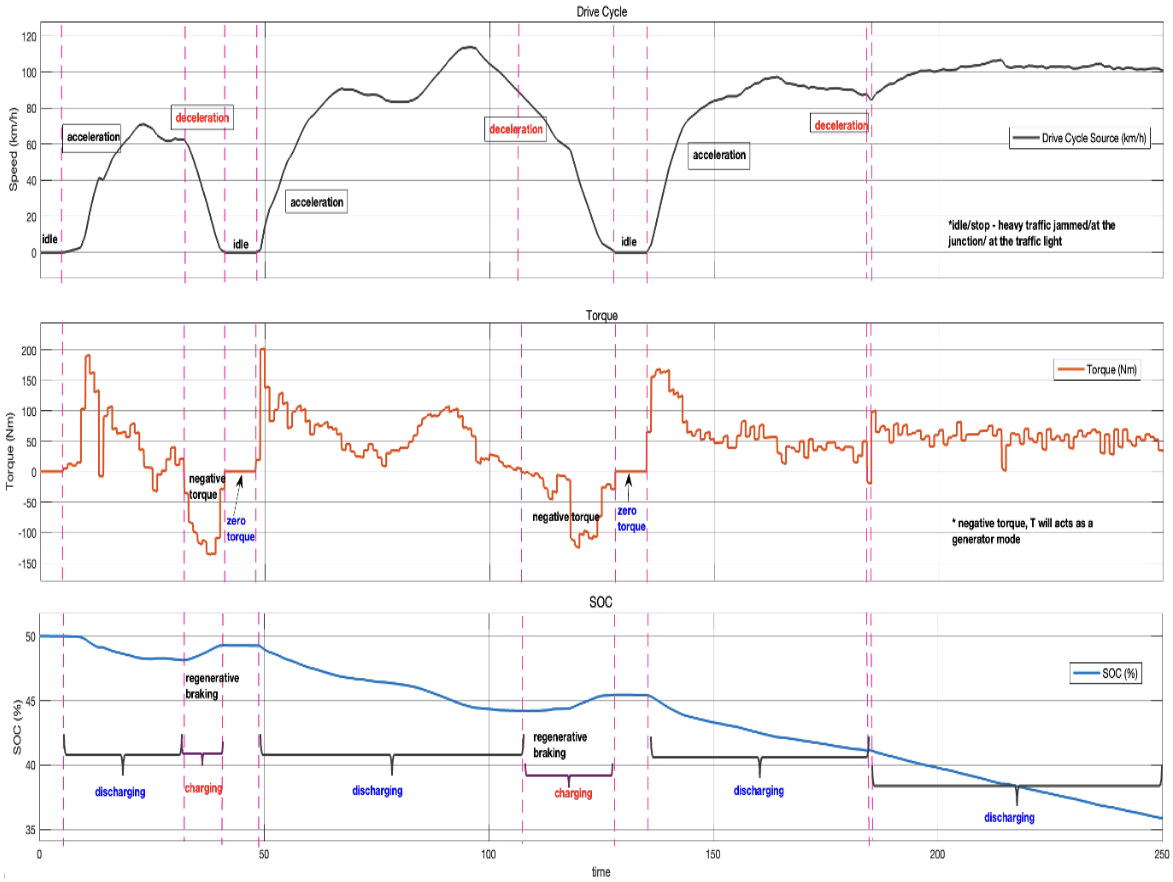

Figure 13. The graphs of drive cycle, torque, and SoC for US60.

In regenerative braking mode, the performance study is conducted separately for a specific level of SOC and speed using a US60 duty cycle. Figure 14 illustrates the details of regenerative braking for two levels of SoC: 80% and 50%. These graphs demonstrate that as the speed decelerates, the torque decreases. While the battery charges, the SoC graph increases, indicating the system is in a regenerative braking state. In both torque graphs, regenerative braking occurs twice between t = 0 s and t = 250 s when the torque is negative.

The increase in SoC (%) during braking, as shown in the graph in Figure 14, can be calculated using the following equation:

$$\mathrm{SoC}\ (\%) = \frac{\Delta Y}{\Delta t} = \frac{Y_2 - Y_1}{t_f - t_i} \times 100\% \quad (9)$$

where Y_2 and Y_1 are the final and initial values on the *y-axis,* and t_f and t_i refer to the initial time and final time.

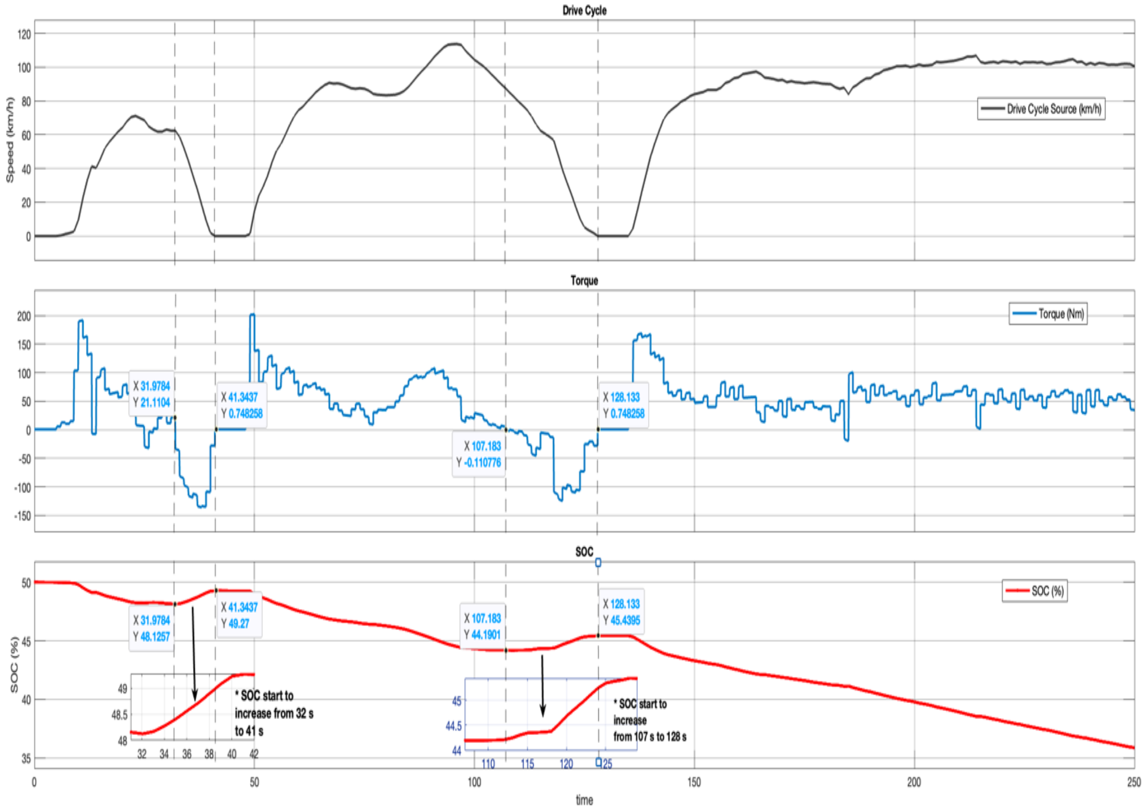

Figure 14. The details graph for regenerative braking occurs between 0 to 250 s for US60.

The results indicate that over a longer duration, the SoC increases slightly more than over a shorter duration. At a 50% SoC level, the first regeneration resulted in a 12.22% increase, while the second regeneration increased by only 5.96%. At an 80% SoC level, the first regeneration achieved a 12.55% increase, while the second regeneration resulted in a 6.19% increase. The summarized results that were obtained are recorded in Table 2. The objective remains to optimize energy recovery and minimize wastage or loss.

Table 2. The percentage of SoC increases during regenerative braking

Level of State of Charge (%)	1st regen	2nd regen
50	12.22	5.96
80	12.55	6.19

The results obtained for both SoC levels show that the percentage increase during each regeneration is similar. Therefore, optimizing energy recovery in both regenerations is feasible. To maximize energy recovery in electric motorcycles, regenerative braking control strategies such as fuzzy logic control (FLC), neural network (NN), adaptive control, and model predictive control (MPC) can be employed. Additionally, implementing these control strategies can enhance the range traveled and reduce rider anxiety.

5. CONCLUSION

In conclusion, regenerative braking is an effective technique for optimizing energy recovery in electric motorcycles. The results from the simulation indicate that using regenerative braking increases the SoC, enabling the generated energy to be stored in the battery for future use. The longer braking periods allow for maximum energy recovery.

Therefore, regenerative braking in electric vehicles represents another technological approach to effective energy management. Additionally, energy recovery through regenerative braking can reduce the overall cost of electric motorcycles and decrease the need for regular maintenance compared to traditional motorcycles.

Once the fundamentals of regenerative braking in electric motorcycles are understood, where the electric motor functions as a generator, future studies should focus on maximising energy recovery during deceleration or braking using braking strategy control, the system can optimize energy usage by reducing consumption while increasing the required energy through the use of various control strategy methods. These control strategies effectively enhance energy recovery. With the implementation of a regenerative braking system controlled by methods like Model Predictive Control (MPC), energy recovery could potentially increase by at least 20% compared to the current systems.

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