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Study of Regenerative Braking System and Brake Force using Pulse Width Module

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Abstract. This paper aims to develop regenerative braking using pulse width module (PWM) control. It concerns frequency of regenerative braking period which is used to control regenerative braking. It is usually restricted by the electric power generation of AC synchronous axial motor. It is measured by motor bench tester. It indicates electronic brake torque and regenerative current. The resistance torque and regenerative current characteristics are expressed as second order polynomial equation. The results present the comparison between pulse signal and full period signal. The maximum deceleration is 10 Hz signal at 2.14 m/s^2, which is not exceed deceleration of brake comfort. The harvest energy at 10 Hz PWM control is 1.40 Wh. It is closely to use full period regenerative brake, but 10 Hz PWM control has comfortable than other frequencies and efficiency is 54.3 percent.

1 Introduction

Today, electric vehicle (EV) is usually powered by electric motor such as brushless DC (BLDC) motor and AC synchronous motor, which are control by inverter. The inverter convert energy from battery to powered motor so that the performance and the driving distance will depend on the battery capacity. The motor can be either actuator or generator. When vehicle is moved by inertia force of vehicle, the motor will be rotated to generate electricity which is charging to battery. It is call known as regenerative braking system (RSB) that it can slow the car [1-3] and it harvests the energy and then it charges to the battery for increasing the driving distance [4,5]. Powertrain system will be bi-directional power flow. RBS performs by using bi-directional because power able to supply power and charge in one system [6,7]. The energy harvest of RBS has some limitations such as speed and regenerative braking current [8,9]. The current charge to the battery so that it obtains as charging current. The maximum charging current depends on battery type [10,11].

Generally, electric vehicle consists of 2 types of braking systems such as mechanical and electrical brake. This research will study electric braking systems. The papers [12,13] studied the development of various control systems for braking force during regenerative energy and electronic brake directly affects to the vehicle movement so that vehicle controller unit (VCU) is required to determine the period of RBS [4].

VCU requires some control systems to perform RBS. There must be a system to control the operation of the brake system. Anti-lock Braking System (ABS) of EV performs that mechanical brake and electronic brake send the brake pulse according to the speed. Normally, ABS will work in case of emergency brake. To encourage brake performance of electric vehicle, mechanical brake system is accompanied with electronic brake force. Thus, anti-lock braking system for electric vehicle using the both brake systems has been presented in the paper [14,15]. The suitable deceleration of vehicle [16] is studied that maximum deceleration on dry road is 8 m/s^2 and uncomfortable of deceleration is between 5-8 m/s^2. The both conditions should be applied to emergency brake. The comfort deceleration should not over then 3 m/s^2.

Electronic brake has been developed for electric vehicle. It has another advantage such regenerative energy. The brake force of battery electric vehicle is enough to stop the vehicle in non-emergency situation. Therefore, this paper developed the regenerative braking control system considering deceleration of vehicle, brake force and regenerative.

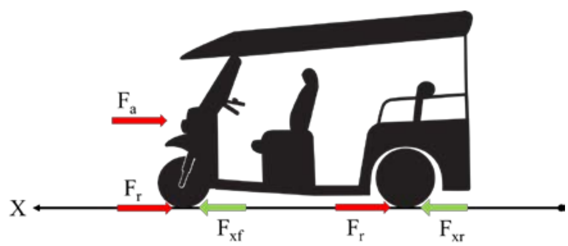

Fig. 1. Free body diagram of tricycle vehicle.

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2 Vehicle system

2.1 Equation of motion

According to longitudinal motion of vehicle [17], the equation of motion can be presented as follows

$$m\ddot{x} = F_T - F_{TR} \tag{1}$$

$$F_{TR} = F_r + F_a + F_g \tag{2}$$

The total resistance (F_{TR}) consists of rolling resistance force (F_r), aerodynamic drag force (F_a), gradient force (F_g). When the vehicle is moving on the road, the tire has been deformed by torque of wheel and road's friction. It causes of the rolling resistance force. It is computed that

$$F_r = F_{r,f} + F_{r,r} \tag{3}$$

$$F_{r,n} = \mu_n m_n g \tag{4}$$

where $F_{r,n}$ denotes the rolling resistance force at wheel n, μ_n is the rolling resistance coefficient at wheel n, m_n is the vehicle mass at wheel n, g is gravitational acceleration constant.

The aerodynamic force (F_a) is occurred, when an object moves through the air. It resists the motion of the object. It depends on many factors, such as front area, shape and speed the vehicle. It is given as

$$F_a = \frac{1}{2}\rho_a C_d A V^2 \tag{5}$$

where ρ_a is the density of air, C_d is aerodynamic drag coefficient, A is frontal area of vehicle, V is speed of vehicle.

$$F_T = \begin{cases} \dfrac{\tau_m}{r_w} & ;\ acceleration \\ -\dfrac{\tau_r}{r_w} & ;\ brake \end{cases} \tag{6}$$

where τ_m denotes torque of motor, τ_r denotes resistance torque of motor.

Considering traction force (F_T), it can produce thrust force or resist force, which depends on control strategies. The motor will produce either driving torque (τ_m) or resistance torque (τ_r).

Table 1. Vehicle Specification.

Specification		Unit
Vehicle		
Wheelbase	2	m
Track width	1.5	m
Weight	600	kg
Gear ratio	5	
Wheel radial	0.3	m
AC synchronous axial motors		
Rated power	3.5	kW
Peak power	10	kW

2.2 Electric powertrain system

The powertrain system obtains a bi-directional power flow as shown in Fig. 2, which consists of 3 main components as listed in Fig. 3 such as battery pack, motor controller and AC synchronous axial motor. The electric current can be supplied to drive the motor and the regenerative braking current from motor is recharged to battery as shown in Fig. 2. The vehicle control unit will decide the task of motor such as actuator or generator.

The battery pack in Fig. 3(a) is compounded of 18650 Lithium ion battery cells. It is designed as 36 series and 7 parallel cells. The specifications of battery pack and cell is presented in Table II. It is designed using non-soldering technique and the pack consists of acrylic cover plates, copper taps and Li-ion cells.

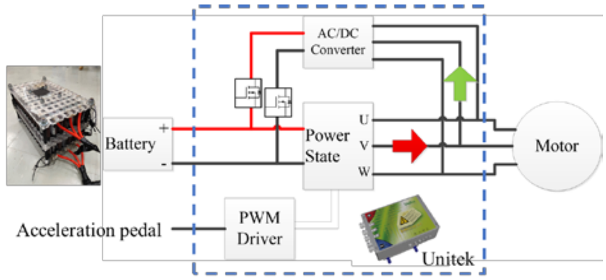

Fig. 2. Bi-directional power flow system of tricycle vehicle.

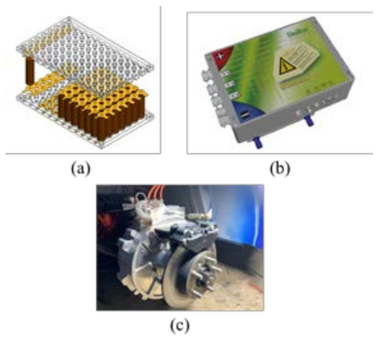

Fig. 3. Components in powertrain system (a) Battery pack
(b) UNITEK Bamocar D3 motor controller
(c) AC synchronous axial motor.

3 Regenerative Braking Control System

The control system consists of component shown in Fig. 4(c). The control system starts from Teensy 3.6 measure data from IMU sensor and generated pulse signal. Pulse signal is pulse width modulation (PWM). NI Myrio is center control unit that it processes signal from any sensor, switch and pulse signal from Teensy to control the enabled period of regenerative braking then operate relay which is connected with UNITEK. The data is record by data logger HIOKI LR8431. It records data from current sensor that measure current between battery and UNITEK shown in Fig. 4(a), hall effect sensor to measure the vehicle speed shown in Fig. 4(b) and regenerative braking signal from relay. The control structure has been presented in Fig. 5.

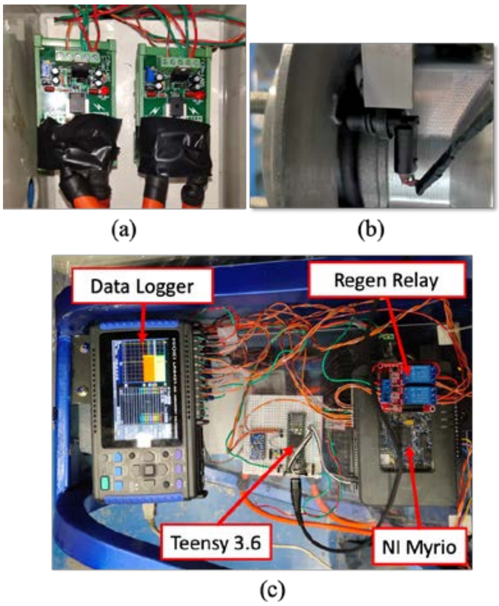

Fig. 4. Components in control system (a) Current sensor (b) Hall effect sensor (c) Control unit and data logger.

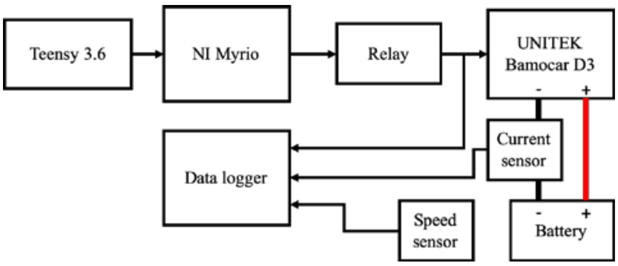

Fig. 5. Structure of control system.

During regenerative braking system, motor will perform as generator where motor coil is rotated, it induces electric back electromotive force (back EMF) and generates resistance torque and transforms the voltage level and current in order to charge battery.

The current and the resistance torque depend on the motor speed. The current must not exceed maximum charging current of battery pack ($I_{ch,max}$) because the overcurrent may harm the battery. The maximum regenerative current can be derived by

$$I_{ch,\max} = N_p \, i_{ch,\max} \tag{7}$$

where, $I_{ch,max}$ denotes maximum regenerative current, which charges to battery pack. N_p is number of parallel cells, $i_{ch,max}$ is maximum charging current per cell.

The resistance torque should not decelerate the vehicle rather than 3 m/s^2 for non-emergency brake because it may disturb passenger's comfort.

Therefore, RBS will be enabled when braking paddle is pushed and the charging current is less than maximum charging current, which can be derived by Eq. (7). The battery specification is shown in Table. II. The maximum charging current equals 28 A for the battery pack.

Table 2. Battery Specification.

Battery Cell	Value	Unit
Nominal voltage of battery pack	129.6	V
Battery pack's Capacity	21	Ah
Number of series (N_s)	36	
Number of parallel (N_p)	7	
Max. voltage of each cell	4.2	V
Nominal voltage per cell	3.6	V
Max. discharge current per cell	20	A
Max. charging current per cell	4	A

4 Electric power generation

Generally, MYWAY is motor bench tester, system of which has shown in Fig. 6. Test motor performed at desire speed, and then load motor generate resistance torque. The test motor will be controlled to increase torque to stabilize the desired speed.

To measure regenerative of AC synchronous axial motors in Fig. 3(c), load motor performs as actuator. Then, regenerative braking system is enabled. The electricity is generated, and it supplies to the tester. Charging current of RBS and resistance torque of test motor are measured at 250, 750, 1000, 1250, and 1500 rpm as illustrated by Fig. 7 and Fig. 8.

As experiment results in Fig. 7 and Fig. 8, the torque and the current characteristics during regenerative braking are similar that the characteristics can be expressed as second order polynomial equation as shown in Eq. (8) and (9). It represents torque of motor during brake as shown in Eq. (6). The solid lines in the figures exhibit the current and the resistance torque when RBS is enabled. The dashed lines illustrate the current and the resistance torque when RBS is disabled.

During regenerative braking system is disabled, the motor is rotated by inertia force of vehicle. The torque and current characteristics are linear. They are slightly increased corresponding with speed. Thus, they seem constant value as the dashed lines in Fig. 7 and 8.

$$I_{ch} = 0.0005\,N^2 + 0.028\,N + 17.434 \tag{8}$$

$$\tau_r = 0.0013\,N^2 + 0.2213\,N + 27.327 \tag{9}$$

where, I_{ch} is regenerative current of axial motor. τ_r is resistance torque of motor. N denotes rotation speed of motor.

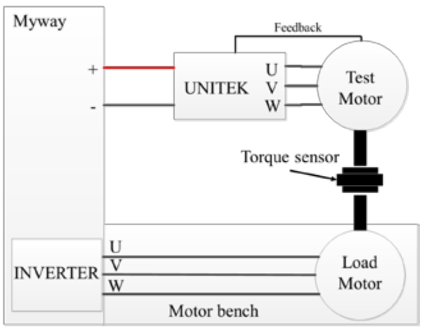

Fig. 6. Motor bench test system.

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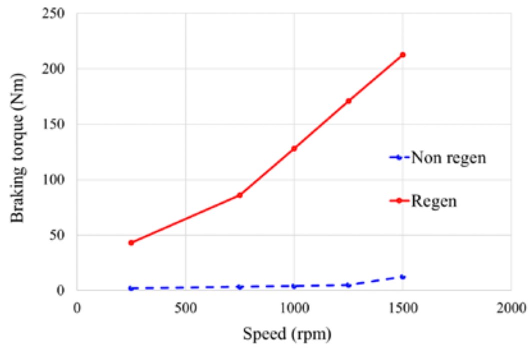

Fig. 7. Torque vs speed between using regen and non regen.

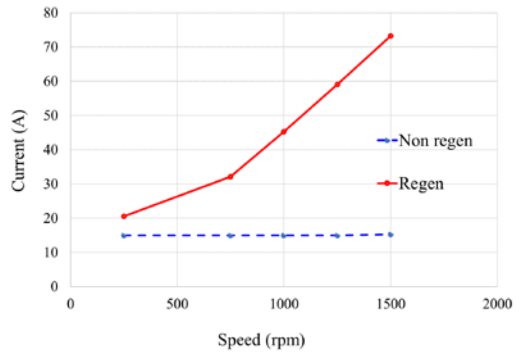

Fig. 8. Current vs speed between using regen and non regen.

5 Experiment Result

The experiment makes a car run straight on a flat road. Then record the data of wheel speed, current, and operating signal of regenerative braking system (RBS). The vehicle accelerates from initial speed to constant speed at 20 km/h, and then the RBS will be started till the vehicle stop. The data are used to compute deceleration and harvest energy. The regenerative braking control signal consist of pulse frequency and full period. Pulse signal form seems as pulse width modulation (PWM) and relates to anti-lock brake system (ABS). The experiment will vary frequency from 1 Hz, 5 Hz, 10 Hz to control regenerative braking system. Full period signal always enables RBS as long as the brake switch is on.

The results of regenerative braking system using 1 Hz, 5 Hz, 10 Hz and full period as shown in Fig. 9. The deceleration of full period, 10 Hz, 5 Hz and 1 Hz are 2.70, 2.14, 2.13 and 1.99 m/s^2, subsequently. The deceleration of 10 Hz signal is closest to full period signal. Harvest energy (E_h) are computed as 1.91, 1.40, 1.28 and 1.55Wh, respectively. Harvest energy at 1 Hz frequency is greater than other frequencies. The energy is only accumulated during the enabled period.

$$\eta = \frac{3600\ E_h}{E_k} \times 100 \qquad (10)$$

Where η is efficiency of regenerative braking system. E_k denotes the kinetic energy of vehicle at constant speed, it equal 9,274.08 J.

The efficiency of regenerative braking system can be derived by Eq. (10), it equal 74.1, 54.3, 49.7 and 60.2 percent, respectively.

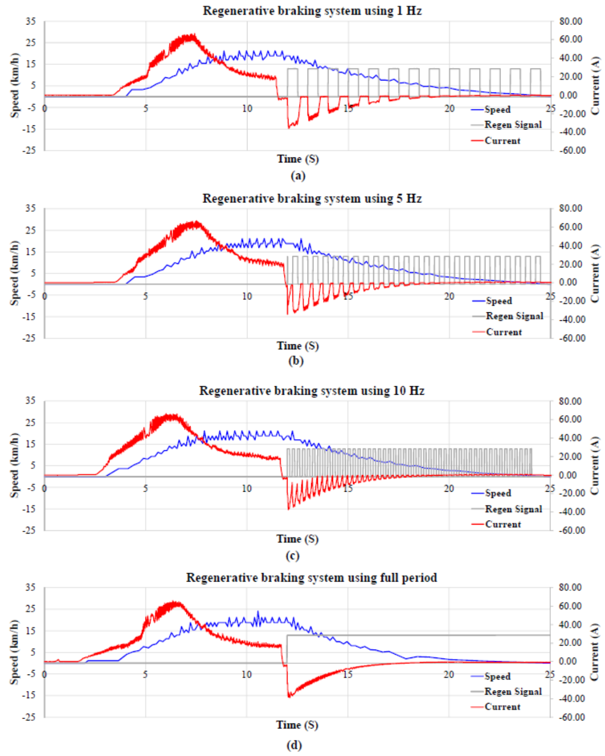

Fig. 9. Experiment result (a) RBS at 1 Hz (b) RBS at 5 Hz (c) RBS at 10 Hz (d) RBS at Full period enable signal.

6 Conclusion

As results, the torque and the charging current characteristics are expressed as second order polynomial equation, when regenerative braking system is disabled, the torque and current characteristics are constant.

Regenerative braking system using full period enable signal has deceleration and energy greater than other pulse frequencies, but brake feel is uncomfortable condition. The harvest energy at 1 Hz enable frequency gets more efficiency, but braking motion has sway motion.

At 10 Hz enable frequency, the vehicle is obtained maximum deceleration at 2.14 m/s^2, which is greater than other frequencies and feeling while braking is comfortable than other frequencies. The harvest energy at 10 Hz enable frequency is between 1 Hz and 5 Hz enable frequencies.

Therefore, the maximum charging current is 28 A and maximum charging current at 10 Hz frequency is 37.51 A that it exceeds the limitation of battery pack in the first period when regenerative braking is enabled. It may damage the battery.

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