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Regenerative Braking for Pedal-Assist Electric Bicycle (Pedelec)

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Abstract: Electric bicycle or e-bike as an alternative transportation would be ideal for fast travel. However, using e-bike has the burden of having short driving range. To address this problem, there have been researches about brake energy recovery technology or the regenerative braking. Regenerative braking is the process of giving the energy from the motor into the battery while in the process of braking. Regenerative braking is common for electric vehicles. However, it is rare on electric bicycles. The aim of this study is to implement regenerative braking system for a Brushless DC motor controller intended for an electric bicycle. a regenerative braking system for a Brushless DC Motor controller for an electric bicycle that consists of a developed microcontroller-based control system for the regenerative braking, a DC-DC boost converter circuit that increases the DC voltage by 10% from the motor that charges the battery and an algorithm for controlling the charging of the battery based from the power generated from the motor was implemented The overall integration of the electric bicycle (BLDC Motor, motor controller, battery), hardware (electronics design), and software (charging algorithm and telemetry) was implemented in this study to successfully employ regenerative braking.

Key Words: BLDC motor; e-bike; microcontroller-based; regenerative braking; boost converter

1. INTRODUCTION

1.1 Background of the Study

Fuel cars produce a lot of carbon emissions which goes to the atmosphere causing pollution and producing greenhouse gases. These problems are continuously growing every day and had already became a great concern globally. Due to this, most industrialized countries seek for an alternative solution to reduce the dependence on oil as their main source of energy. As an alternative solution, electric vehicles such as an electric bicycle is gaining attention (C. Hua, 2013). E-bike as an alternative transportation would be ideal for fast travel. However, using electric bicycles has the burden of having short driving range. Increasing the distance that the electric bicycle can travel is important. For an electric bicycle, its main source of power is the battery which is one of the major factors in addressing the problem of electric bicycles having short driving range (Yanan. G, 2016). To address this problem, there have been researches about brake energy recovery technology or the regenerative braking (P. Gupta, 2014). Regenerative braking can add 5-20% efficiency but an average rider on a normal road can get 10% further distance on a single battery charge.

Regenerative braking is the process of giving the energy from the motor into the battery while in the process of braking. The inertia of the vehicle then forces its motor to function as a generator. While in this process, the battery acts as a load thus providing the braking force of the electric vehicles (Xiaohong Nian. F, 2014). It has many advantages such as increasing the range it can travel. It also allows the battery to be charged especially when downhill thus, decreases the charging time of the battery which saves more energy hence helping the environment.

1.2 Review of Related Literature

There are several journals related to the topic of regenerative braking for electric vehicles as well as for electric bicycles. This section will show the difference of the related topics from those published journals and articles with regards to this study.

A related study created a fuzzy logic model (FLmRB) for regenerative braking for electric vehicles which uses the vehicles acceleration and jerk, and the road inclination as its input variables. This output shows the percentage energy retrieved from the braking process to the battery. The aim of this study was to create electric vehicles using manufacturers intellectual property data and avoids the use of on-board sensors of the electric vehicles. A Mamdani FIS (Fuzzy inference system) was used to model the existing regenerative braking system control strategies in order to map the input variables and the regenerative ratio. This study proved that the proposed model for regenerative braking system, which is the FLmRB, successfully inferred the regenerative braking factor from the measurements of the electric vehicles acceleration, and road inclination (R. Maia and Nunes, 2015).

Another one created a study for regenerative braking of BLDC motor for light electric vehicle. A power converter or boost converter is not used in the study. Instead of using two current sensors, the DC-link transmission line with single current sensor is used to measure both motor winding current and charge current in the closed loop system. This study has no current and voltage sensor, hence no power flowing into the battery will measured. It also lacks a speed sensor which can measure the speed for controlling of the braking distance which our study will provide. Our study will also provide a current and voltage sensor in order to measure the power, a step-up DC-DC boost converter which is controlled by a PWM in order to maintain the output current which is also connected to a MOSFET for a fast switching to stabilize the charging, and a braking control to control the electronic and mechanical brake (Jiaqun and Haotian, 2015).

Another study presented BLDC motor control that utilizes the PID control, as well as the distribution of braking force that adopts a fuzzy logic control. With the fuzzy reasoning that is slower than the PID control, the braking torque can be real-time controlled by the PID control. By comparing this solution to different ones, this is identified to have better performance in regard to realization, robustness and overall efficiency. Implementation of the study is the needed improvement for this study as it is critical in determining on whether the equations made throughout the study is possible for actual situations (Xiaohong Nian and Zhang, 2014).

Also, a study implemented regeneration system on electric vehicles using lead acid battery. For this study, there is an on-off switch provided to control the power of the motor, while for our study, the controlling of both electronic braking and mechanical braking will be done to manipulate the use of regenerative braking (Angeles, 2015).

1.3 Objectives

This study aims to implement regenerative braking system for a Brushless DC motor controller intended for an electric bicycle. To implement this, a DC-DC boost converter circuit will be developed which would increase the DC

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voltage by 10% from the motor to charge the battery. Finally, the study aims to develop an algorithm for controlling the charging of battery based from the power generated from the motor.

2. METHODOLOGY

The overall integration of the electric bicycle (BLDC Motor, motor controller, battery), hardware (electronics design), and software (charging algorithm and telemetry) was implemented in this study to successfully employ regenerative braking.

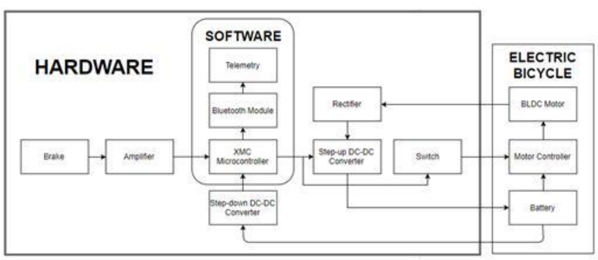

Fig. 1. System Block Diagram

The microcontroller used was XMC4700 Relax Kit which contains all the necessary specifications, peripherals and devices needed for the implementation of the system such as ADC, Digital I/O, UART, SYS Timer and others. A voltage sensor was also connected to the XMC. The software Dave App was used to program the microcontroller. A Ratiometric Hall Sensor A1302 was used to employ a proportional analog output for the brake to specify its level of depression. The analog output of the brake was amplified from 2.4V to 3.3V so it would read its value precisely since its input voltage limit is 3.3V. When the brake is triggered, it will automatically disconnect the motor from the motor controller through the switching circuit. As a result, the motor will run as free-wheel. A Bluetooth module was connected to the microcontroller to implement a wireless connectivity to the Smartphone which will serve as telemetry. It will state the voltage output from the motor and boost converter, brake and the actual PWM. The connections used in the motor controller were throttle, brake control, 3-phase connection, DC supply and hall sensors.

2.1 Design Considerations

The regenerated energy will depend on the level of depression of the brake. To employ a proportional analog output for the brake, a magnet was placed near the A3102. The analog output of the brake was amplified which served as analog input to the XMC microcontroller. Using its analog input, it will compute for the PWM which will be fed to the boost converter. It will determine how much current will be fed back to the battery.

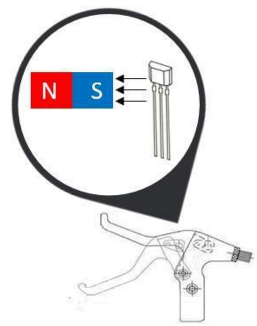

Fig. 2. Modified Electric Bicycle Brake

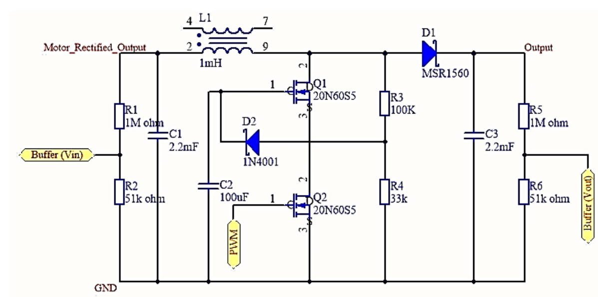

Fig. 3. High – powered Boost Converter

The components used in Fig. 1 circuit includes a 1 mH Leaded inductor with a rating of 10 amperes, the MSR1506 diode which was originally designed for boost converters, two (2) series connected 20N60S5 MOSFETs in, a 1N4001 diode which is connected to the voltage divider and to the Gate of the first MOSFET, a 100 µF capacitor connected to the Gate of the MOSFET, and the 100
volts 2200 µF capacitor. The battery acts as the load for this boost converter circuit.

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$$\text{Duty Cycle} = (1 - V_{in}/V_{out}))*100\% \quad \text{(Eq. 1)}$$

where:

V_{in} = Input voltage

V_{out} = Output Voltage

To compute for the duty cycle or the pulse width modulation (PWM), Eq. 1 was used. Thus,

$$\text{Duty Cycle} = (1 - 30/53))*100\% \quad \text{(Eq. 2)}$$
$$= 43.40\%$$

The needed PWM modulation to boost the input of 30V to 53V is 43.4%. This PWM modulation will be achieved if the brake is depressed by at least 70%. If the brake is only depressed by 10% then the output PWM from the XMC is 4.34%. The PWM will come from the microcontroller which is programmed to have a desirable output. The DC output voltage of the motor will serve as the input of the boost converter. The output of the motor, which is 48 volts, will be boosted up to 53 volts to be able to charge the 48-volt battery. In this circuit, the PWM controls the boosted output voltage. When the PWM increases, the boosting of the circuit also increases however at some point of modulation the boosted voltage will decrease. There is a maximum voltage which can achieve more or less 50 percent.

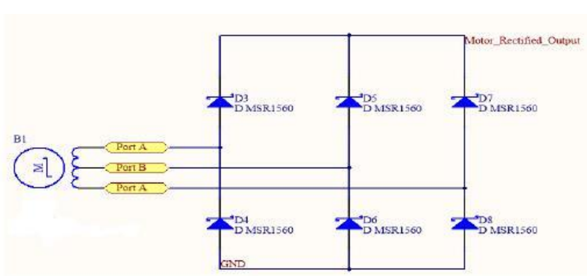

Fig. 4. Three-Phase Rectifier Circuit

The output of the BLDC motor is connected to a 3-phase diode rectifier to have a DC voltage at the output. The diode used in the designed circuit is MSR1506 which has a rating of 600 volts and 15 amperes. This diode is a soft recovery diode with Low Reverse Recovery Charge and Peak Reverse Recovery Current. This circuit converts a three-phase AC voltage at the input to a DC voltage at the output. The output voltage should be in DC to be able to connect to the designed DC DC boost converter circuit.

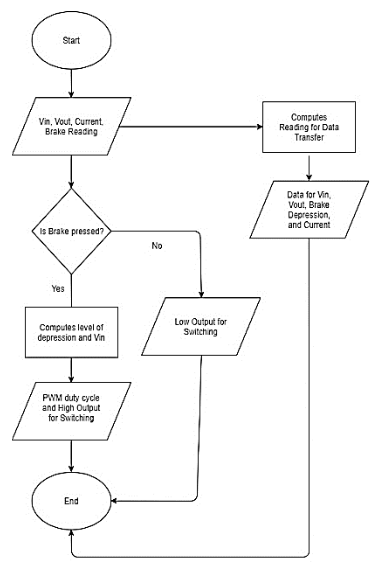

Fig. 5. Charging Circuit Algorithm

The program implemented in the XMC is one of the vital parts of the system. The program will start by reading the input and output voltage from the battery, its current reading, and the analog output of the brake. Afterwards, it will compute the reading for the data transfer using from XMC to Smartphone enabled through the Bluetooth module, and it will also detect if the brake is being pressed. If the brake is pressed, the XMC will compute for its level of depression and V_{in} for data transfer. Moreover, the data gathered will be used for the computation of the PWM duty cycle. The switching circuit will have HIGH output which will turn off the motor controller, then the boost converter circuit will be enabled. The boosted voltage will depend on the level of depression of brake. However, if the brake is not pressed, the output for switching would be LOW therefore, the boost converter circuit is OFF.

3. RESULTS AND DISCUSSION

The DC-DC boost converter steps up the voltage from its input at the supply to its output at the load. In the boost converter developed in this paper, the input voltage comes from the motor of the e-bike. This input voltage should be increased or boosted by 10% to be able to have an output voltage which would charge the battery. Table 1 shows the 10% boosted voltage of the circuit and its percentage error.

Table 1. Theoretical input voltage (V_{in}) and output voltage (V_{out}) for the Boost Converter

Theoretical V_{in}	Theoretical V_{out}
23.00	25.56
24.00	26.67
25.00	27.78
26.00	28.89
27.00	30.00
28.00	31.11
29.00	32.22
30.00	33.33
31.00	34.44
32.00	35.56
33.00	36.67
34.00	37.78
35.00	38.89
36.00	40.00
37.00	41.11
38.00	42.22
39.00	43.33
40.00	44.44
41.00	45.56
42.00	46.67
43.00	47.78
44.00	48.89
45.00	50.00
46.00	51.11
47.00	52.22
48.00	53.33

Table 2. Experimental input voltage (V_{in}), output voltage (V_{out}) for the Boost Converter and the Percentage Error

Experimental Vin	Experimental Vout	Percentage Error
23.08	25.87	1.23%
24.15	26.73	0.24%
25.04	27.78	0.01%
26.16	28.92	0.11%
27.12	29.81	0.63%
28.01	30.99	0.39%
29.06	32.03	0.60%
30.06	32.81	1.57%
31.03	34.53	0.25%
32.08	35.68	0.35%
33.06	36.81	0.39%
34.02	37.55	0.60%
35.05	38.67	0.56%
36.06	39.80	0.50%
37.00	40.86	0.61%
38.04	41.68	1.28%
39.09	42.81	1.21%
40.04	43.87	1.29%
41.02	45.06	1.09%
42.03	46.11	1.19%
43.09	47.35	0.90%
44.03	48.42	0.96%

45.05	49.50	1.00%
46.02	50.59	1.02%
47.07	51.74	0.92%
48.08	52.89	0.83%

Table 1 and 2 shows that the input voltage of 23.08V was boosted to an output voltage of 25.87 compared to the theoretical output voltage of 25.56V with an error of 1.23%. The voltage of the motor which was 48.08V was boosted to an output voltage of 52.89V with an error of 0.83%. In principle, the actual charging voltage of the 48V battery is at 53V. The 52.89V acquired from the experimental data comes close to the required charging voltage.

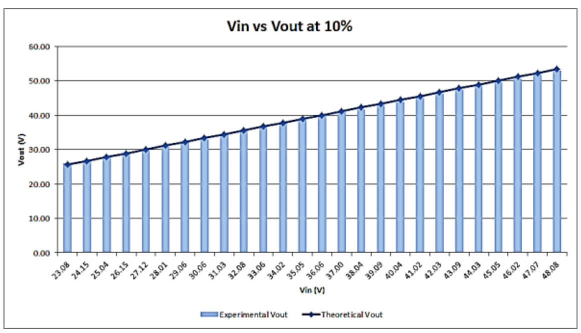

Fig. 7. V_{in} boosted at 10% PWM (Theoretical vs Actual)

Fig. 7 shows the graphical representation of the data gathered for the boosting of the output voltage by 10%

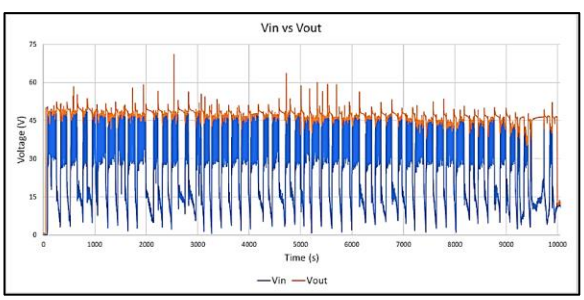

Fig. 8. V_{in} vs V_{out} running at 15 kph

Figure 8 shows the input voltage generated by the motor and the output voltage of the boost to charge the battery. When the speed is 15 kph the average input voltage from the motor is around 25V-30V. This input voltage was boosted every time the bike was depressed. Even if the brake was depressed the depression should reach to at least 65% to charge the battery to reach a voltage of around 47V.

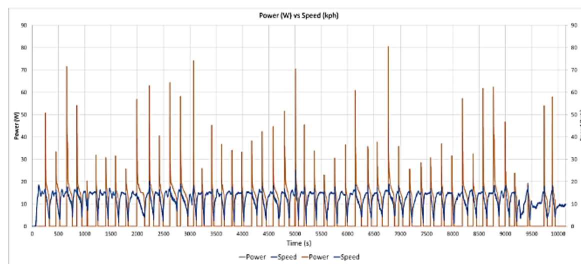

Fig.9. Power Output at a single run

Fig. 9 shows the power output at a single run from full charge which is 50V to low charge which is 47.5V. Since there are only 10 braking points, there only 10 instances where there is an output current from the boost converter to charge the battery. The highest output power recorded is 82.99 W. When braking, the output power kicks in because there is already current passing to charge the battery. The higher the speed before braking, the higher the kick in of the power. When the speed goes down, the output power also goes down.

4. CONCLUSIONS

Through the duration of the study, a regenerative braking system for a Brushless DC Motor controller for an electric bicycle which consists of a DC-DC boost converter circuit that increases the DC voltage by 10% from the motor that charges the battery was implemented. A DC-DC boost converter circuit steps up the input voltage coming from the DC output voltage of the motor to its output at the load. The output voltage of the motor is 48V and is increased by 10% and boosts to 53V therefore enables the battery to charge. As shown in Table 1, the lowest percentage error attained was 0.01% coming from an input voltage of 25.04V to a boosted output voltage of 27.78V and the highest of 1.57% that shows the input voltage of 30.06V that was boosted to an output voltage of 32.81V. The maximum boosted output voltage attained was 52.89V which comes close to the required charging voltage of 53V.

For this study, in order to have a more desirable output in the boost converter circuit, a higher PWM frequency that reaches up to MHz in value is recommended. In accordance to this, it lowers the value of the V_{ds} in the MOSFET which in result, avoids the fluctuations in the output. A modular regenerative braking circuit that will be compatible to electric bicycles is best advice for publicizing and innovating the system of electric bicycles.

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