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Regenerative Braking of Hub Type Brushless Direct Current Machine Used on Electric Bicycle

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Abstract

Electric motors are more efficient than internal combustion engines. This puts forward electric vehicles more popular than fossil fuel vehicles. However, electric vehicles have limited range because of insufficient batteries. For this reason, studies focus on increasing the range of electric vehicles. Regenerative braking is a solution that helps this problem. In this study, a new regenerative braking modeling was recommended and applied on a brushless direct current machine (BLDC) of electric bicycle. Energy recovery is attained at the different speeds by means of the recommended model. The modeling results were compared with the application results and they verified each other. The analyses have showed that gain and efficiency which attain from the regenerative braking increased at higher speeds of hub type BLDC. Ultimately, the energy recovery of 6.37% was saved by means of the regenerative braking of the hub type BLDC used on electric bicycle at 320 RPM.

Keywords: Electric bicycle, electric vehicle, energy saving, hub BLDC, regenerative braking

1. Introduction

Today, the main energy sources are fossil fuels for vehicles [1]. Due to oil crisis, their environmental pollutions and exhaustible characteristics, fossil fuels are desired to replace with alternative energy sources [2]. In this way, countries will also be able to reduce their dependence on oil [3]. These developments will make electric vehicles a popular subject with the addition of new studies in this field.

Electric vehicles have several advantages such as low emission, high efficiency and silent operation [4]. However, their limited range of battery systems prevents to become more common [5]. Internal combustion engines (ICEs) are used to move in traditional fossil fuel vehicles, but electric vehicles utilize electric motor for moving [6]. This makes possible regenerative braking which is impossible in ICE's [7].

Regenerative braking is a system that helps increasing the range of electric vehicles [8]. Braking is made with friction by the mechanical way in traditional vehicles. Brake pads rub on rotating disc when the speed deceleration is wanted. Meanwhile, the kinetic energy of rotating wheels converts into heat energy and dissipate environment [3, 9]. The regenerative braking system (RBS) allows the energy save while stopping the electric vehicle. Electric machine in the electric vehicle starts working as a generator when the braking command is taken. Energy flow occurs into battery and this energy is stored [10]. Thus, system efficiency is increased besides the range of electric vehicle. Amplitude of back electromotive force (EMF) generated during regenerative braking changes with motor rotation speed. Therefore, the generated voltage should be boosted at low speeds for storing energy to the battery [11, 12]. This situation can be solved with a boost converter.

Regenerative braking is an effective method in deceleration and generation of energy, but it is not proper to use alone as brake. Therefore, it should be used with mechanical braking. Because RBS is not effective at low speeds and it may not stop the vehicle during an electric fault [13].

When the literature is examined, some studies related to regenerative braking are seen. These studies generally

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mention about the energy attain from regenerative braking. There was a study about the braking torque which aim and succeed increasing efficiency [1]. But there was an additional braking system in this study. In another study, several switching methods were applied to a brushless direct current machine (BLDC) and stopping time and gained energy were researched. However, that was only done for two speed values [6]. A study investigated the current that flows into battery during regenerative braking. The current flowing into battery was measured for nine different speeds and an inference was made about the regeneration current and speed [2]. However, the obtained voltage during regenerative braking was increased with different method instead of an external boost converter. There was also a research that increased the regenerative braking voltage with an external boost converter. Consumed and recycled energy were measured for five different speeds. But that research was not done with a hub BLDC machine [9].

In this study consist of RBS modeling and application for a hub type BLDC machine which using on electric bicycle. A new model realized in MATLAB/Simulink has been verified with a real implementation setup. The obtained voltage during regenerative braking increased with an external boost converter. By means of this study, how much energy save was realized was determined as percentage for certain speed and certain motor working period when regenerative braking is executed on the hub type BLDC machine. The energy recovery that obtained from the regenerative braking was clearly observed at different speeds. A considerable amount of energy recovery was achieved.

In the first part of this study, a general subject introduction is indicated. After mentioning the used materials in the second part, how simulation and experiment studies were done are explained in the third part in detail. In forth part, the findings and interpretation are presented about the experiment and application results. Inferences from the study are specified in the fifth part.

2. Materials

2.1. Brushless Direct Current (BLDC) Machine

One of the most important parts of electric bicycle and other electric vehicles is the electric machine that provides movement. BLDC machines are the most used machines in electrical vehicles [14]. Especially, the hub type BLDC machine is the most preferred one [3]. The hub type BLDC machines consists many poles in the stator [15]. Therefore, they can generate higher torque values. This machine has some advantages such as high efficiency, noiseless operation, low maintenance and long operation life [11]. In BLDCs, electronic commutation is applied via driver [16, 17]. The location of rotor can be obtained by means of hall effect sensors. Three hall effect sensors are enough in three phase BLDC machines. Switching equipment is triggered after sensors signal is processed according to the angle value [18].

2.2. BLDC Driver

Switching is done with the help of driver. There are totally six semiconductor switching equipment's in three phase BLDC machine and each phase take two of them [10]. The basic equivalent circuit of BLDC driver is presented in Figure1.

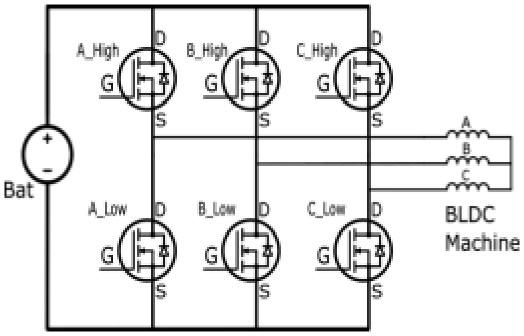


Figure 1. BLDC driver basic equivalent circuit.

There are six switching conditions according to signals that obtained from hall sensors in BLDCs. Triggered switching equipment's according to the hall sensors are given in Table 1.

Table 1. Triggered switching equipment according to the hall sensors.

	Hall Sensor Signals			Switching Equipment		
	A	B	C	A	B	C
1	1	0	1	High	Low	
2	1	0	0		Low	High
3	1	1	0	Low		High
4	0	1	0	Low	High	
5	0	1	1		High	Low
6	0	0	1	High	Low	

2.3. Boost Converter

The generated voltage which attained from the hub type BLDC machine during regenerative braking is not higher than the battery voltage for charging. A boost converter is required to do that illustrated in Figure 2.

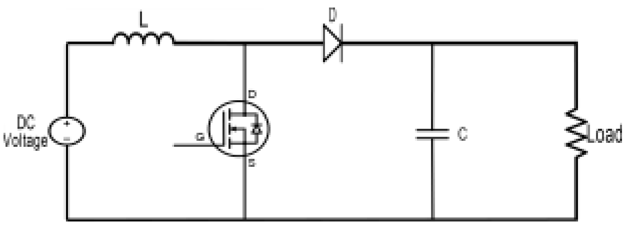
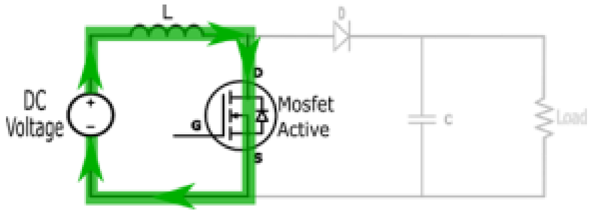


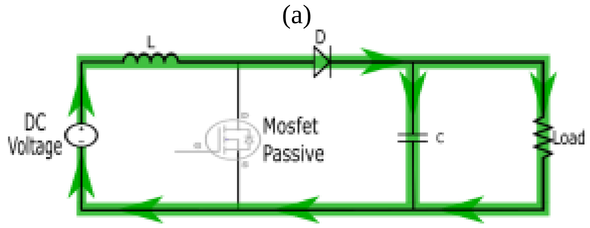
Figure 2. Boost converter basic equivalent circuit.

3. Method

In this section, a simulation and application of RBS applied to a hub type BLDC machine used on electric bicycles is presented. The hub type BLDC machine was worked as a motor for 12 seconds. At the end of this period, it was stopped with RBS. Gained energy from RBS and consumed energy of system were measured and how much recycling were been achieved was calculated as percentage.



(a)



(b)

Figure 3. witching Equipment (a) turned on (b) turned off situation.

3.1. Simulation

The simulation studies were carried out in MATLAB/Simulink. A system overview is illustrated in Figure 4.

In simulation modeling, a “Permanent Magnet Synchronous Machine” block was chosen as a component that provide movement. Phase number was adjusted three. Back EMF shape was selected trapezoidal. Torque was chosen as the mechanical input. Stator phase resistance was chosen 0.01 Ω, stator phase inductance was chosen 250 µH, inertia was 0.1344 kg×m2, viscous damping was 0.084 N × m × s, pole pairs was 23, static friction and initial condition was zero. 120° was entered for Back EMF flat area. Flux leakage generated by magnets was selected as machine constant and 0.023354 was entered.

The hub type BLDC machine works as a generator for 12 seconds in simulation. Energy was provided by battery. Battery type was selected lead-acid and adjusted 36 V. Energy which provided to the hub type BLDC machine is cut out at the end of period via switches that located output of driver. Simultaneously, the switches which located input of the boost converter are closed. Meanwhile, the hub type BLDC machine which continues rotate work as a generator and induce voltage in the coil terminals. Induced voltage is increased to higher level than battery via boost converter. Thus, current is occurred from the hub type BLDC machine into the battery and energy is stored in battery. Battery acts like a load during regenerative braking. Therefore, rotation ends quickly.

3.2. Application

Test bench was set up around of the hub type BLDC machine that is used in electric vehicles. The hub type BLDC machine starts operating as a motor for 12 seconds with start command. Energy flows to the hub type BLDC machine from battery via driver circuit during this period. Relays in relay board replace the contacts to another position after 12 seconds is expired. Thus, connection between driver and the hub type BLDC machine is cut out. The hub type BLDC machine is connected to three phase rectifier. Voltage is induced on the coils of the hub type BLDC which continues rotation and energy is generated at the same time. Generated energy is stored after it is directed into three phase rectifier and boost converter. The open circuit scheme of system designed for application is presented in Figure 5.

Three phases hub type BLDC machine was used during application. The system setup is shown in Figure 6. Eight cables were used of the hub type BLDC machine. Three of them were thicker than other five and those were phases cables. Three of five were reserved for sensors that determine rotor position. The remaining two cables were used to energies sensors and they were supplied with 5 V. The signals which were come from sensors were processed with STM32F07VG electronic board. The STM32F407VG electronic board gives outputs according to the written code. Those outputs provided movement of the hub type BLDC machine.

Energy was supplied to system by batteries. Batteries were selected lead-acid type. System control was realized with the STM32F407VG control board. That electronic card was coded with own library in MATLAB/Simulink. Real time data can be sent from board to computer by means of UART module.

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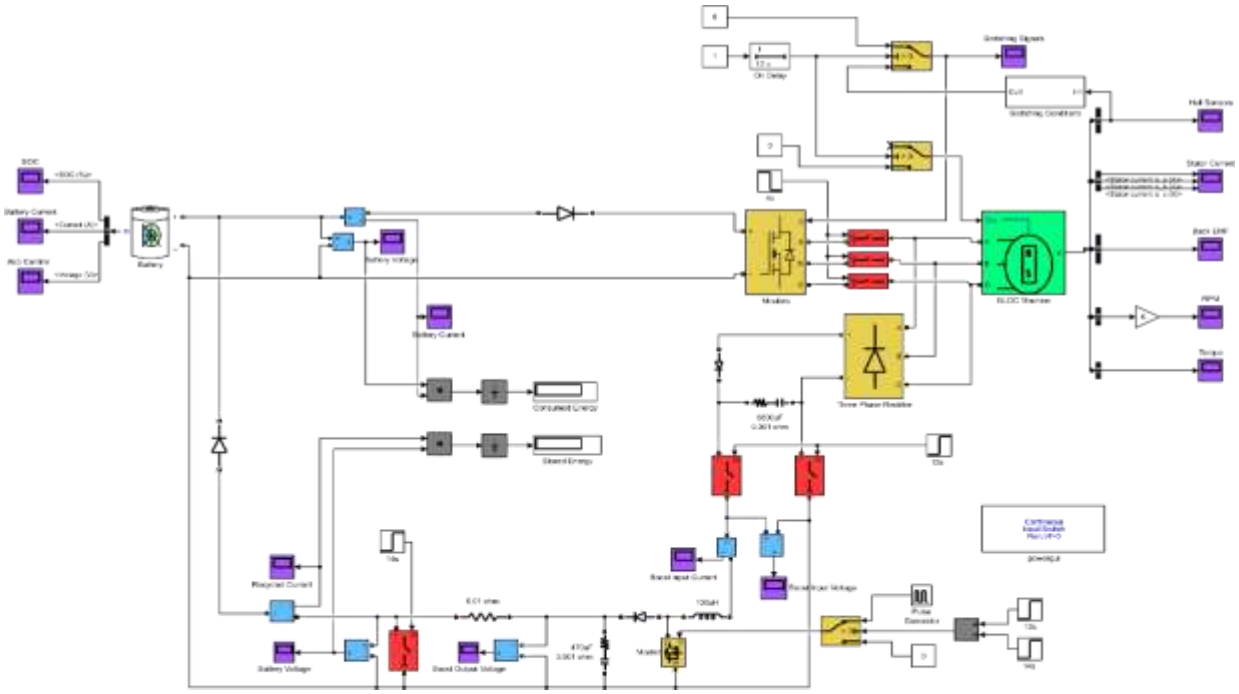

Figure 4. System overview.

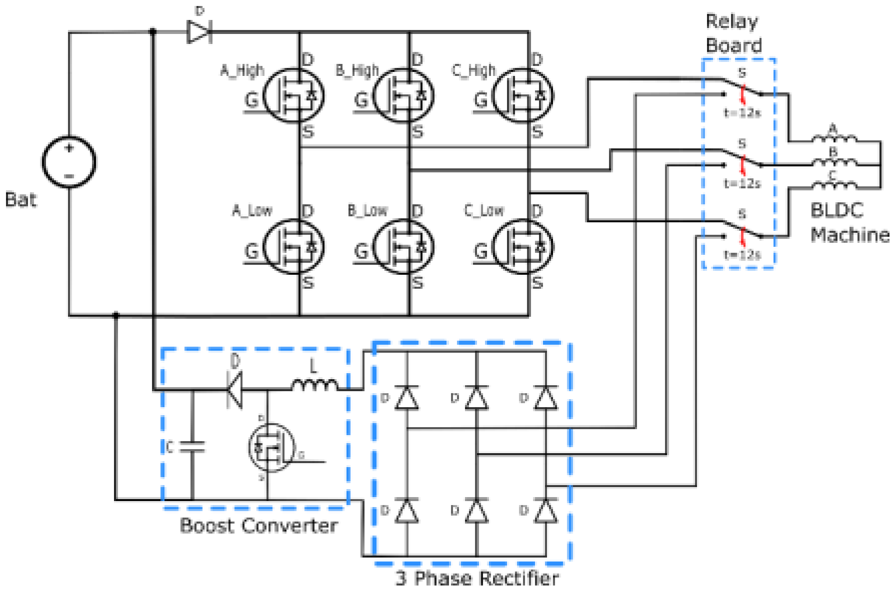

Figure 5. Designed system scheme.

The STM32F407VG control board sent required data's to driver circuit for movement of the hub type BLDC machine. Semiconductor switching equipment's were turned on in accordance with signals which transmitted driver circuit. The hub type BLDC machine coils was energized via semiconductor switching equipment with the signals that implemented to driver circuit and then movement was begun.

The V connector in the driver circuit shown in Figure 6 is input of energy that to be transferred from battery to motor. A, B and C terminals were connected to the hub type BLDC machine phases. IR2104 D1-D3 elements were half bridge motor drivers. OC1-OC6 symbolized opto-couplers and 6N137 was selected as opto-coupler. The control board sent data's to IR2104s via opto-couplers to rotate motor. Terminal 1 was used to supply energy for IR2104s. They were supplied with 12V. Terminal 2 was used to energies for opto-couplers. 5V was given to the terminal.

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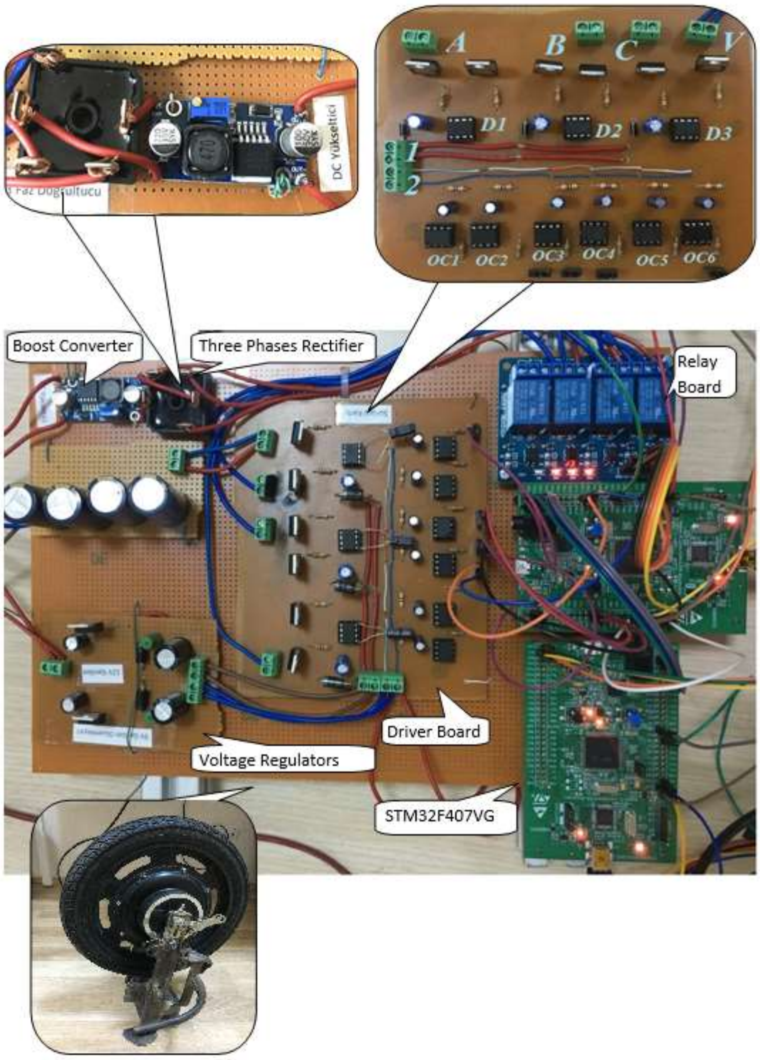

Figure 6. The system setup.

75NF75 mosfets were used as a semiconductor switching equipment in driver. IR2104 half bridge motor drivers were preferred to turn on mosfets. VCC pin in IR2104 was supplied by terminal 1. The capacitor that was connected between VB and VS was necessary for turning on high side mosfet. Their values were 47 µF 50 V. The diode that was connected between VCC and VB prevented the reverse current which could be occurred from the capacitor. The diode code was SB560. VS connector of IR2104 was connected one of the motor phases in other words one of A, B or C terminals. HO and LO connectors of IR2104 were used to turn on the high and low side mosfets. Both IN and SD inputs needed to be logic 1 to activate HO. IN logic 0 and SD logic 1 needed to be implemented to activate LO.

Driver board and control board were connected via 6N137 opto-couplers to protect driver for the reason of any short circuit or fault situations. Therefore, totally six opto-couplers were used for each one of inputs (IN and SD) of the driver. Dual opto-couplers were available in the markets but they had higher propagation delay time. There were also opto-couplers which have slower propagation delay time but they were more expensive than two 6N137. Due to their advantages, 6N137 was selected for using on driver. 6N137 opto-couplers propagation delay time were at the level of nanoseconds. They turned off when their input logic 1 otherwise they turned on.

Pin 8's and pin 5's of opto-couplers were supplied by terminal 2 of driver circuit. RL = 300 Ω and RM = 75 Ω were selected for opto-couplers. Bypass capacitors values were selected 0.1 µF 50 V. Pin 2's and pin 3's connected to control board. Pin 6's were connected IN or SD input of IR2104's. Pin 7 signal was conveyed to pin 6 according to the input signal of 6N137. Due to supplied voltage levels of pin 8's of 6N137's and inputs

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(IN and SD) of IR2104's were same, pin 8's and pin 7's of 6N137's were short circuit.

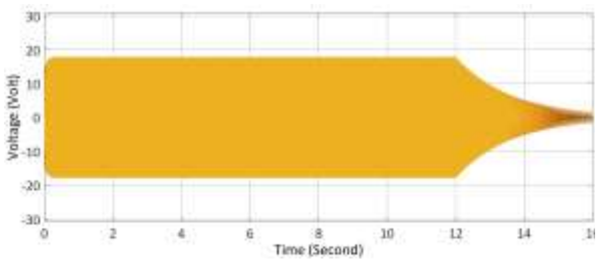
All the system was energized with batteries, but all equipment's could not be supplied with the same voltage level. There should be different voltage levels in system for the hub type BLDC machine, opto-couplers, half bridge drivers and sensors. Therefore, some equipment's should be supplied via voltage regulators. There were two voltage regulators, 5V and 12V, in the system. LM2576HVT-5.0 P+ and LM2576HVT-12 P+ components were used to obtain 5V and 12V.

4. Results & Discussion

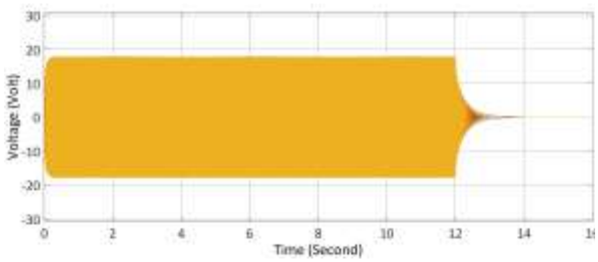
4.1. Simulation Results

The simulation study of RBS for the hub type BLDC used on electric bicycle was carried out for 16 seconds in MATLAB/Simulink. The hub type BLDC machine was worked as a motor during 12 seconds. Regenerative braking was executed after 12 seconds. Simulation system did not contain any other braking mechanism except RBS. Thanks to this simulation study, it was possible to monitor certain parameters such as battery and BLDC parameters.

First, the stopping effect of RBS was desired to observe. The hub type BLDC machine back EMF's are illustrated in Figure 7. Figure 7a shows the back EMF's when the RBS is passive and Figure 7b shows the back EMF's when the RBS is active.



(a)



(b)

Figure 7. Back EMF's for RBS is a) passive b) active.

Back EMF occurred as long as the hub type BLDC machine rotates. So, it means that BLDC was stopped when the back EMF was damped. Figure 7a shows that BLDC stops after a slowdown that takes a few seconds. If the Figure 7b is analyzed, the graphic drops sharply at 12th second and BLDC stops before one second is up.

The second observed situation was the energy recycling. When the charge status of the battery used in the system was examined, it was seen clearly whether there was energy recycling or not. The state of charge (SOC) of the battery is presented in Figure 8.

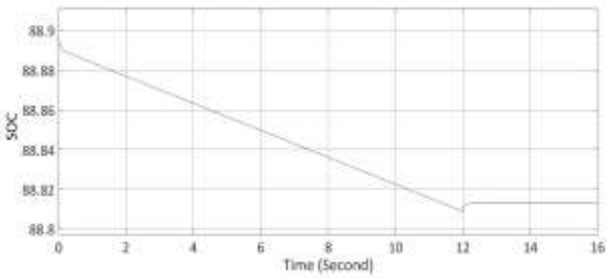


Figure 8. The state of charge of the battery.

At the beginning of system working lots of energy was taken from battery. Due to starting current of electric motors was high that was not an abnormal situation. After the starting, the SOC of battery decreased linearly until 12th second. That means the hub type BLDC machine rotated at a constant speed. The battery was stored energy for a short period after 12 seconds. That short period shows that the occurred regenerative braking. If the graphic is examined carefully, most of the energy stored during regenerative braking is made in the first moments of regenerative braking. After a short time, the increase ended and the SOC remained constant level. This means that regenerative braking was over. After this moment, there was no change in the SOC. This indicated that he hub type BLDC machine was stopped.

4.2. Application Results

The hub type BLDC machine used in electric vehicle was run as a motor for 12 seconds in this application. End of this period, the signal was sent to relays and them was changed contact position and regenerative braking was applied. BLDC machine was idle while it was working as a motor. Battery current and voltage values were measured to calculate consumed and stored energy. The experiments were repeated at different speeds.

Current-time graph of battery is given according to BLDC speeds in Figure 9(a)-(h). Figure 9a-d is obtained under conditions where three identical batteries were used in system. Figure 9e-h presented graphs of the situations which the system was supplied by two identical batteries. In Figure 9a, starting current of motor was nearly 7 A. BLDC need 600 mA in idle working situation. Regenerative braking was implemented after 12 seconds from motor starting. The current which was transferred to battery was measured approximately 1 A during regenerative braking. When Figure 9b was analyzed, the starting current of motor was seen higher than 1 A and regenerative braking current was 900 mA. Figure 9c showed that idle current supplied from batteries was upper than 300 mA. The current obtained by means of regenerative braking was 100 mA at the end of 12th seconds. Figure 9d which motor speed was 109 RPM indicate that BLDC extracted 250 mA from battery. The saved current was about 50 mA during regenerative braking. In Figure 9e, starting value of current was roughly 12 A, idle current was 500 mA and regenerative braking current was 800 mA. When Figure 9f was examined, the hub type BLDC saved 1.8 A at the start. Batteries provided 400 mA in the idle working. Current was measured 200 mA after 12 seconds. There was no current at the negative side in Figure 9g and Figure 9h. This means that the system could not save energy to the batteries at the speeds of 84 and 45 RPM.

This study included the simulation and application of regenerative braking in the hub type BLDC machine used on electric vehicle. The hub type BLDC machine was operated as a motor for 12 seconds. It rotated at 317 RPM. The system was supplied by 36V lead-acid battery. At the end of 12 seconds, the energy flowed to the motor was cut off with the help of switches and regenerative braking was applied. The energy obtained from the regenerative braking was stored in the battery via increasing the voltage level with the help of a boost converter.

The hub type BLDC used on electric bicycle was operated as an idle motor for 12 seconds in application. The values of 320, 237, 160, 109 RPM were achieved by means of changing PWM signals which trigger driver. Meantime, the system was supplied by the three identical 12 V lead-acid battery connected in series. The system also was supplied by two identical 12 V lead-acid battery connected in series. Meantime, the tests were done with the values of 212, 142, 84 and 45 RPM. At the end of 12 seconds, regenerative braking was applied to the hub type BLDC with the help of the relay contacts changing position. The obtained energy was stored in the battery group by means of a rectifier and boost converter.

In the simulation study, the regenerative braking was applied to the hub type BLDC machine that rotated for 12 seconds at 317 RPM and 6.21% energy recovery was achieved. In the application, the regenerative braking was applied to the hub type BLDC machine rotating for 12 seconds at 320 RPM speed and 6.37% energy recovery was achieved. MATLAB/Simulink simulation has been verified to compatible with real system setup.

5. Conclusion

In this study, a simulation study was performed in MATLAB/Simulink for regenerative braking of a hub type BLDC used on electric bicycle. Its results were confirmed by an application setup. The consumed and saved energy were calculated by means of measuring current and voltage of battery in this simulation. The hub type BLDC has been rotated at 317 RPM for 12 seconds and energy recovery of 6.21% was achieved when applying the regenerative braking on the hub type BLDC. A stopping effect occurred by regenerative braking was seen clearly at BLDC machine. During the application studies, the battery current and voltage values were measured to calculate the recycled energy values. The application was carried out for different speed values. It was observed that the current drawn from the battery increased as the speed of the BLDC increased. It was also determined that the current generated by the regenerative braking decreased as the speed value decreased. The recycling rates were calculated with the measured currents and voltages. These were 6.37% at 320 RPM, 5.15% at 237 RPM, 0.57% at 160 RPM, 0.19% at 109 RPM, 3.3 % at 212 RPM and 1.34% at 142 RPM. It was noted that he recycling rates were 0% at 84 and 45 RPM since no current flowed to the battery. According to these data, the rate of recycling decreased when the BLDC speed decreased. Finally, the study showed that the regenerative braking of the hub type BLDC used on electric bicycle was a system that could be used more effectively at high-speed applications.

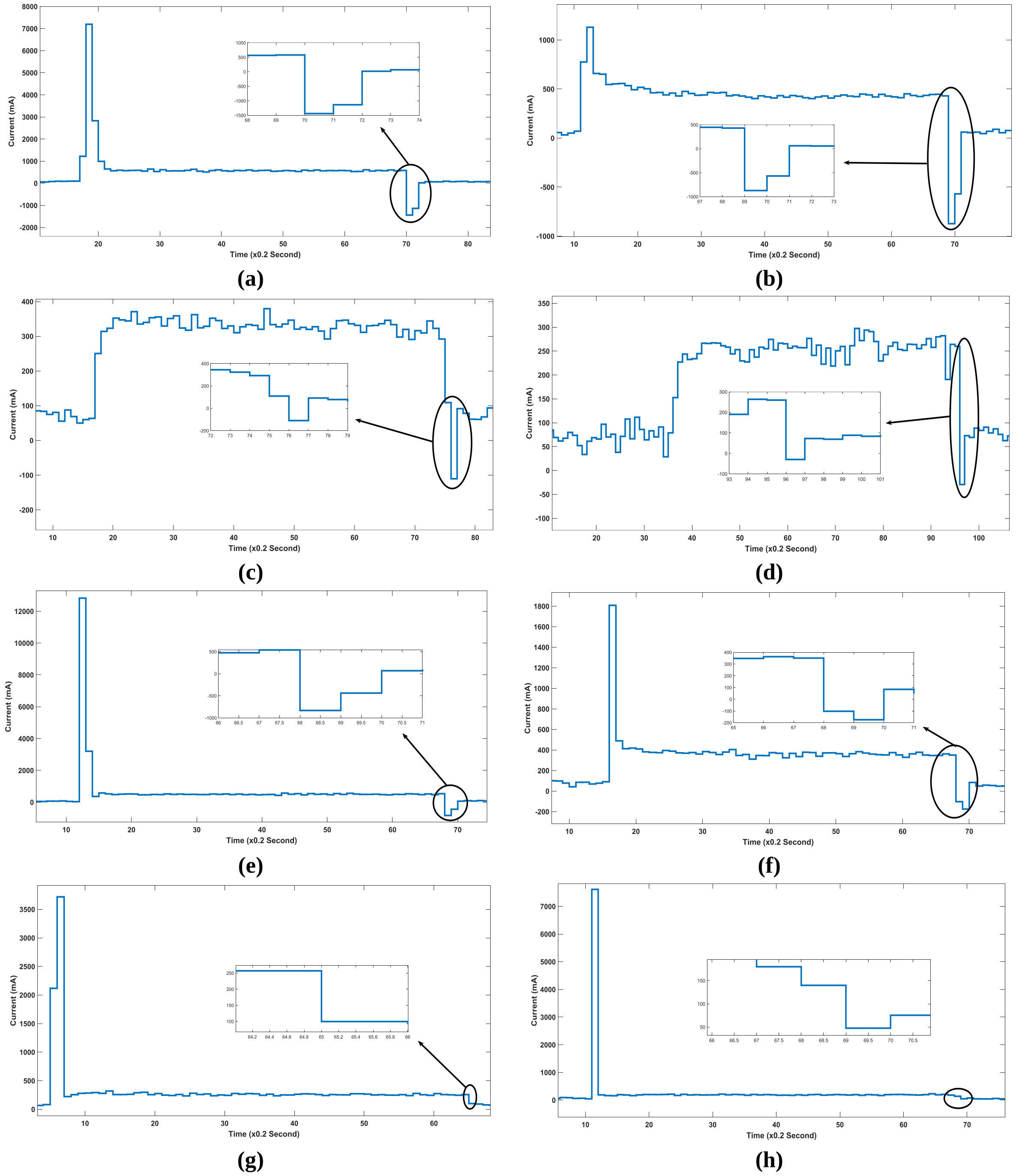


Figure 9. Current-time graphs at the value of (a) 320, (b) 237, (c) 160, (d) 109, (e) 212, (f) 142, (g) 84 and (h) 45 RPM.

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Author Contributions

Alper Kağan CANDAN: Drafted and wrote the manuscript, performed the experiment and result analysis.

Hayati MAMUR: Assisted in analytical analysis on the structure, supervised the experiment's progress, result interpretation and helped in manuscript preparation.

Ethics

There are no ethical issues after the publication of this manuscript.

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