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Research Article

MATLAB/Simulink Modeling of Regenerative Recovery Circuit with Bidirectional DC-DC Converter for Scooter

Ali Sinan Çabuk[1*],

[1*]Istanbul Technical University, Electrical Engineering Department, 34469, Maslak, Istanbul, Turkey. (e-mail: ascabuk@itu.edu.tr).

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Corresponding author: *Ali Sinan Cabuk*

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ABSTRACT

Scooter, which is in the class of light electric vehicles, is a very common transportation vehicle, especially in big cities. Brushless direct current motor (BLDCM) is preferred in scooters. These motors are a type of electric motor used in light electric vehicles (LEV) due to their features such as high efficiency, long operating life, high speed and silence operation. Although the BLDCMs used in the propulsion system of the scooter have high efficiency, they do not have a long range due to their limited battery capacity. The biggest problem with scooters is their short range. In order to solve this negativity, manufacturers are working on different solutions.

In this study, MATLAB/Simulink modelling of bidirectional DC-DC converter regenerative recovery circuit for scooter was carried out. It is aimed to increase the range with regenerative recovery. The system in the proposed study is implemented for a 300W BLDCM with a rated voltage of 24V. The effect of bidirectional DC-DC converter regenerative recovery is proven by MATLAB/Simulink results.

1. INTRODUCTION

Today, electric vehicles are used to reduce the increasing environmental pollution problems. Small and light electric vehicles (LEV) are preferred in large cities with dense population. Scooters are widely used in today's big cities as LEV. The range of electric vehicles is limited by their battery capacity. An electric vehicle with widely used batteries today has a shorter range. However, the battery charge time required for the electric vehicle to start again is quite high. In order to eliminate these disadvantages mentioned in electric vehicles, the energy in the battery should be used efficiently [1-3]. There are many methods used in the literature to increase the range of electric vehicles. Among these methods are increasing the efficiency of the electric motor, using different mechanical designs and using the regenerative braking method. These methods are used in all electric vehicles. In recent years, scooters have been widely used due to their practical use and the absence of traffic problems [4, 5]. Methods of optimizing electric motors and using different mechanical designs are the methods used to increase the range of scooters. However, the use of regenerative braking, which is one of these methods, is not preferred by the manufacturers in scooters that have a lot of use in urban transportation.

The purpose of the regenerative braking method is to transfer the energy produced in the electric motor during braking of the vehicle to the battery group. Thus, the vehicle has the opportunity to store a certain amount of an energy in the battery while driving. The energy is used again for the movement of the vehicle. Thus, the range value of the vehicle is increased.

The electric motors used in scooters are direct drive motors. The movement taken from the motor is designed without using any powertrain. Hereby, external rotor electric motors are preferred in scooters. The Brushless Direct Current Motor (BLDCM) is the most widely used in scooters. BLDCM controls are made with two methods, with and without sensors. In both methods, power electronic elements and microprocessor are used. The regenerative braking method used in BLDCM is unique to every electric vehicle. It is unique because of the power circuit components and software used [6].

Microprocessors suitable for Digital Signal Controller (dsPIC), Peripheral Interface Controller (PIC), Digital Signal Processing (DSP) and Sliding Mode Control (SMC) structure are used in sensor control algorithms. dsPICs are capable of stable, fast and high-resolution detection. In addition, it is preferred for regenerative control of electric motors used in electric vehicles, as it has special Pulse Width Modulation (PWM) channels for motor control [7, 8]. However, it is seen that the output of the microprocessor cannot provide sufficient current in the use of dsPIC. Therefore, motor driver integration is used between the processor and semiconductor power electronics elements [9]. dsPIC needs the speed information obtained from the hall sensor and the data it receives from the current sensor in sensor control methods for system control [10]. It is important to use SMC as a control algorithm in regenerative systems using PIC. The SMC algorithm assists in detecting the time variation of BLDCM resistance and inductance values with temperature or other factors [11]. DSP is a special microprocessor that converts input signals from analog to digital and performs calculations on the signals more efficiently. One of the biggest advantages of DSP is that it allows system parameters to be easily changed to adapt to the application. Regenerative recovery circuits created with DSP are more complex than others. It has a more advanced architecture as software [12].

Sensorless algorithms are based on the back-EMF principle. The zero crossing points of the back-EMF are obtained by comparing the phase at the section with the star point. In some regenerative recovery systems, the back-EMF method is not preferred due to the noise and error rate in the signal. The noise and error rate in the signal create high torque vibrations. Therefore, vector control is preferred in system control. DSP is generally preferred in applications performed with Field Oriented Control (FOC). When the control is performed with FOC, the control algorithm is complex and the processor load is high. In such applications, DSP is used even if the software is complex [13, 14].

In this study, MATLAB/Simulink modeling of regenerative recovery circuit with bidirectional DC-DC converter for scooter is implemented. In the literature and applications, regenerative recovery system design has been found on the scooter, which is in the category of light electric vehicles. The outer rotor BLDCM used in electric scooters has been the focus of this study to fill this gap in the literature. In order for the BLDCM to work in the regenerative braking zone, the necessary control algorithm has been developed and the power electronics circuit has been modeled. The BLDCM used in the study has a rated power of 300 W, 24-36 V and a speed of 2120 rpm. Electronic circuit simulation was carried out with the LTspice software to determine the switching elements and other electronic elements that can be used in the driver circuit. The necessary algorithm for the control of the driver circuit and the test of this algorithm have been made. The model of the system required for the regenerative recovery circuit and the transfer of the recovered energy to the battery was created with the MATLAB/Simulink software. Recovery in scooters, which are frequently used in daily life, is an incomplete issue in the literature. In this study, the design of the bidirectional DC-DC converter regenerative recovery circuit, which is not included in the literature, has been realized.

2. PROPOSED SYSTEM MODEL

The outer rotor BLDCM works in 4 zones. BLDCM needs to operate in the regenerative braking zone for regenerative state. These regions are shown in Figure 1. The first quarter is the forward acceleration zone. This is the quarter positive speed-positive torque situation. The second quarter is the reverse braking zone. This is the quarter negative speed-positive torque situation. The third quarter is the region of reverse acceleration. This is the quarter negative speed-negative torque situation. The fourth quarter is the forward braking zone. This quarter is the positive speed-negative torque situation [15]. By changing the direction of the phase current in the regenerative braking region, a negative force is applied to the BLDCM. In this case, since the direction of the current is towards the battery, the mechanical energy of the motor can be stored as electrical energy.

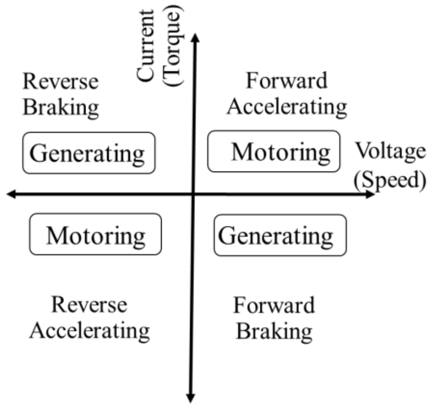

Figure 1. Quadrants of Operation Using a BLDCM [15]

If the switching sequence is set to reverse the direction of the current, the BLDCM will operate in the braking zone. The force to be applied to the motor can be adjusted in the opposite direction by adjusting the PWM. The operating zone of the BLDCM is determined by controlling the switching signals. This control is provided by the microprocessor. The signals received from the processor are transmitted to a driver circuit and transferred to the trigger terminals of the switching elements. The structure of the system is as in Figure 2.

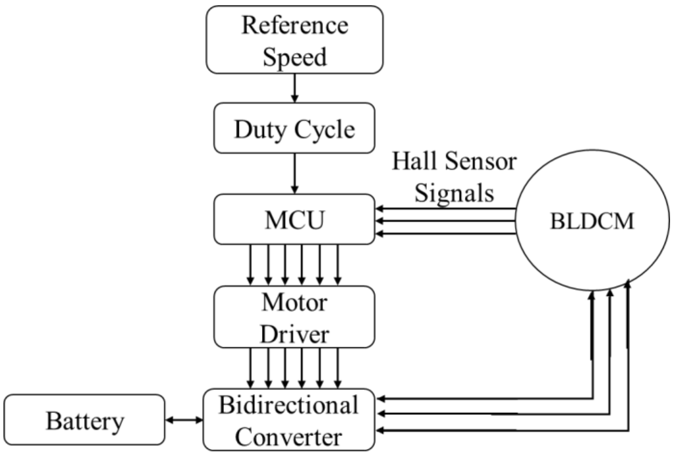

Figure 2. System Flow Diagram

The BLDCM is powered by the DC bus voltage, but the current is controlled by commutation stage semiconductor switching elements. The commutation time is determined by the rotor position. Rotor position is detected differently in sensorless and sensored motors. In this study, since sensor control is preferred, rotor position is obtained with hall sensors. When permanent magnets on the rotor surface pass by the hall sensors, the position of the rotor is known by giving a 0-1 digital signal. The digital signal string is transmitted to the microcontroller. This data is compared with the reference speed with the control algorithm. According to the comparison result, the PWM signal is generated. The digital code sequence coming from the hall sensor changes according to the rotation direction of the motor. The microcontroller controls the bidirectional converter according to which quarter mode the BLDCM operates.

The truth tables for the operation of the motor operating zone and the regenerative braking zone are as in Tables 1 and 2 [9, 16].

TABLE I
MOTOR OPERATING ZONE

Step	Hall Signals			Switching Signals					
	H1	H2	H3	S1	S3	S5	S2	S4	S6
I	1	0	1	0	0	1	0	1	0
II	1	0	0	1	0	0	0	1	0
III	1	1	0	1	0	0	0	0	1
IV	0	1	0	0	1	0	0	0	1
V	0	1	1	0	1	0	1	0	0
VI	0	0	1	0	0	1	1	0	0

TABLE II
REGENERATIVE BRAKING ZONE

Step	Hall Signals			Switching Signals					
	H1	H2	H3	S1	S3	S5	S2	S4	S6
I	1	0	1	0	0	1	0	1	0
II	1	0	0	1	0	0	0	1	0
III	1	1	0	1	0	0	0	0	1
IV	0	1	0	0	1	0	0	0	1
V	0	1	1	0	1	0	1	0	0
VI	0	0	1	0	0	1	1	0	0

2.1. Simulation of LTspice Circuit

The LTspice program was used to determine the current and voltage values and waveforms of the BLDCM driver of the proposed system. It is necessary to know the electrical characteristic Equation (1) of the motor for BLDCM driver design [17-19].

$$\begin{bmatrix} V_a & -e_a \\ V_b & -e_b \\ V_c & -e_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

where *V* is the voltage applied to the stator windings, *e* is the EMF formed in the stator windings, *R* is the phase winding resistance of a phase, *i* is the current passing through the winding, *L* is the stator winding inductance, *M* is mutual inductance and *a*, *b*, *c* phase windings.

The driver circuit designed with the LTspice program is shown in Figure 3. There are six IRF540N type MOSFETs in the inverter circuit. The drain-source voltage of this MOSFET is 100V and the continuous drain current is 33A. This MOSFET is suitable for fast switching as its input parasitic capacitance is low.

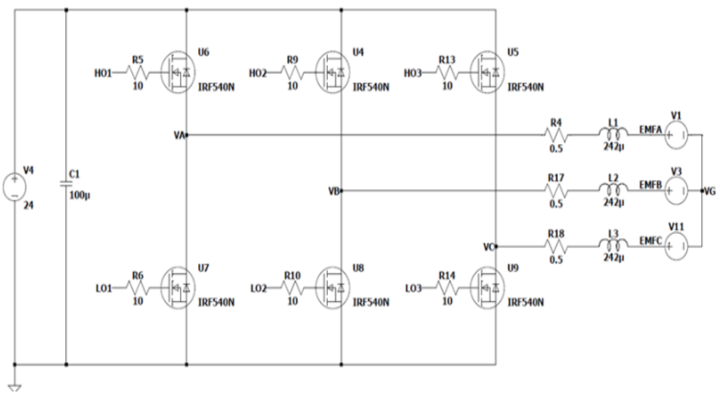

Figure 3. LTspice Model of Driver Circuit

BLDCM's back EMF waveform is designed as trapezoidal. There is a 60º phase difference between the trapezoidal waves seen in Figure 4.

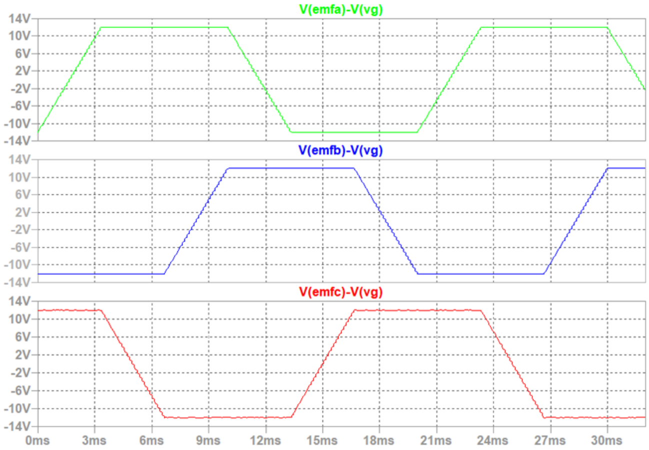

Figure 4. Back EMF voltages of phases A, B and C

The maximum and minimum values of the voltage depend on the speed of the motor and the voltage coefficient. Commutation is performed electronically in BLDCM. In the proposed circuit, 120º square wave commutation is implemented. Phase currents are shown in Figure 5. While the BLDCM phases are energized, the current passes through one phase and returns from another phase. In this case, there is no energy in the third phase. This process is carried out in accordance with a certain phase sequence and the movement of the motor is provided.

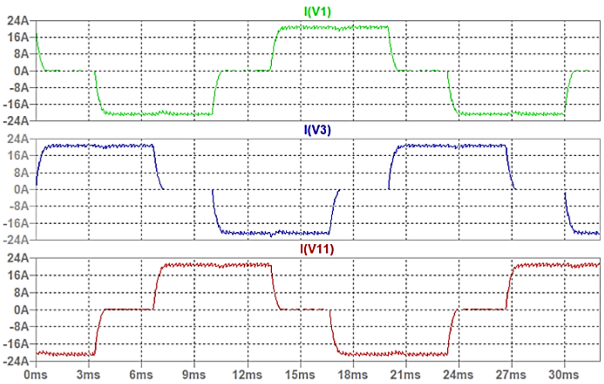

Figure 5. Phase currents A, B, C for 90% pulse width

It was observed that the phase current increased when the percentage of pulse width increased. This means more braking torque. Equation 2 is used to calculate the braking torque and compare the torque produced at two different pulse widths [17-19].

$$T = \left(e_a . i_a + e_b . i_b + e_c . i_c\right) / 2\pi f \quad (2)$$

where *f* is the frequency. *e* is the back EMF voltage of the phase, *i* is the phase current. *a*, *b* and *c* represent phases A, B and C. The electromagnetic torque produced by the BLDCM is as in Equation 3 [17-19].

$$T_e = {K_t}/{2}\ (e(\theta_r) i_a + e(\theta_r - {2\pi}/{3}) i_b + e(\theta_r + {2\pi}/{3}) i_c \quad (3)$$

where K_t is torque constant and θ_r is the rotor angle. Braking torque is given by Equation 4 [20].

$$T_{break} = K_t . i \quad (4)$$

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The output torques at 50% and 90% pulse width are compared for the increase of the braking torque specified in Equation 2. Figure 6 shows the electromagnetic torque.

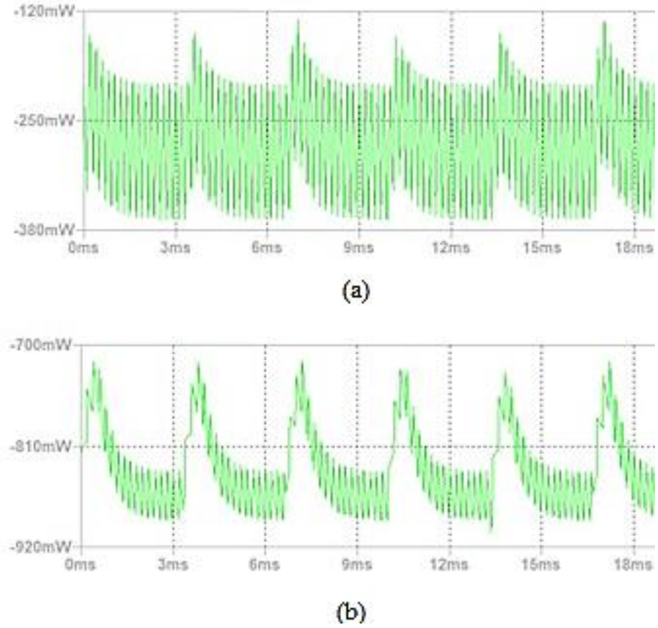

Figure 6. Electromagnetic Torque of BLDCM a) 50% pulse width b) 90% pulse width

It is seen that an average braking torque of 0.275 Nm is obtained in the case of 50% pulse width. An average braking torque of 0.834 Nm is produced at 90% pulse width. The braking torque produced increased when the percentage of pulse width was increased.

3. MATLAB/SIMULINK MODEL

In the study, outer rotor BLDCM, which is preferred by many scooter manufacturers, was used. The subject of the study is the BLDCM hall sensor. The parameters of the motor are given in Table 3.

TABLE III
PARAMETERS OF BLDCM

Parameter	Value
Power [W]	300
Voltage [V]	24
Speed [rpm]	2120

3.1. Bidirectional DC-to-DC converter

A bidirectional DC-to-DC converter is circuit that enables the conversion of DC power in both directions. It is commonly used in applications where power needs to be efficiently transferred and shared between two systems or energy storage devices. The bidirectional converter frequently consists of control circuits and power semiconductor switches. The control circuitry puts in order the switching of the semiconductor switches to acquire the target power flow direction and efficiency. It ensures that the power is warrantably interchanged between the input and output. Moreover, the converter contains feedback loops, control algorithms and protective features. The bidirectional DC-DC converter has many advantages. These are voltage regulation, energy efficiency and power flow control. It enables efficient energy transfer between different voltage levels or energy storage devices, enabling functions such as battery charging, discharging and power sharing between multiple sources or loads.

In the proposed system, there is a bidirectional DC-DC converter between the inverter and the battery as in Figure 7.

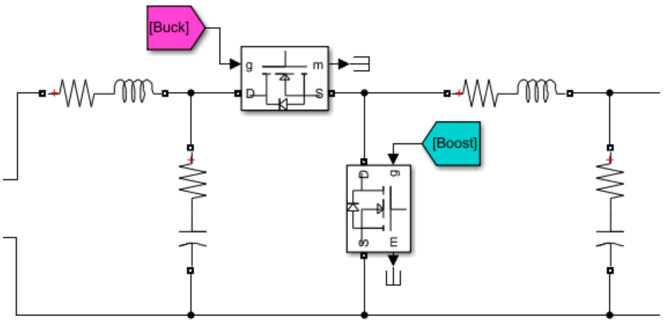

Figure 7. Bidirectional DC-to-DC Converter

When the motor is running in the forward direction (forward acceleration zone), the bidirectional converter works as a Buck DC-DC converter. In the regenerative braking state, the bidirectional converter works as a Boost DC-DC converter. Thus, bidirectional energy flow is provided both from the battery to the BLDCM and from the BLDCM to the battery. Another advantage of the bidirectional DC-DC converter is that the DC input voltage of the inverter can be adjusted. Thus, the speed control of the motor can be realized and the pulse width setting of the switch used in the step-down converter operating state is changed.

3.2. Inverting Block

The inverter block used for electronic commutation is given in Figure 8. This block consists of six power switching elements. Each switch has a control input. The data received from the Hall sensors are processed in the controller block and the order and duration of the power switches are set.

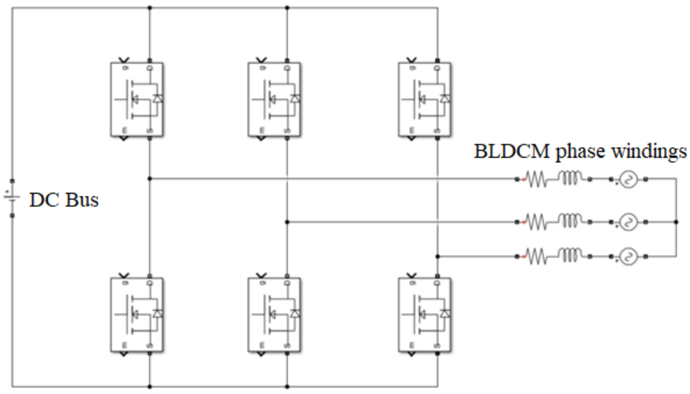

Figure 8. The Inverter Block and Motor Phase Windings

3.3. Controller

The internal structure of the controller block is shown in Figure 9. There are three basic structures in the controller block. These are inverter control, step-down converter control and step-up converter control. In the inverter control, the model in Table 1, which is used in the motor running condition, has been created.

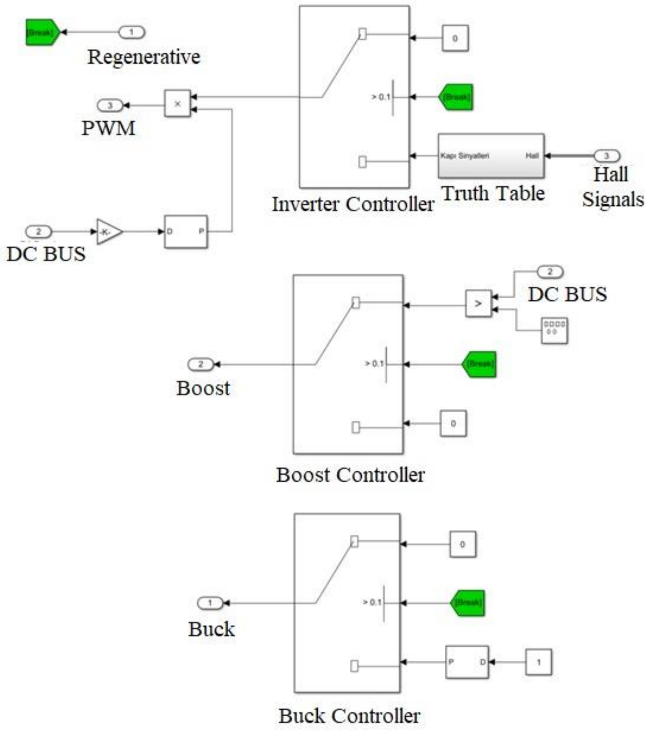

Figure 9. Controller Blocks of The System

The switching elements of the inverter go to turn-off with the signal to switch to the braking state to the controller. In the case of regenerative braking, reverse parallel connected diodes in the structure of the switching elements act as uncontrolled rectifiers and rectify the voltage induced in the motor and transfer it to the DC bus.

In the buck converter controller, the voltage of the DC bus can be adjusted by lowering the voltage in the battery. In the boost converter control, the DC bus voltage is compared with a saw-toothed signal and the control signal of the boost converter is produced. The battery is charged by increasing the voltage in the DC bus.

3.4. MATLAB/Simulink model of the system

A MATLAB/Simulink model of the system was created to find the energy transferred to the battery while the outer rotor BLDCM was operating in the regenerative braking zone. In this model, a bidirectional DC-DC converter is used to transfer the recovered energy to the battery and feed the vehicle in motor mode. The MATLAB/Simulink model of the proposed system is as in Figure 10.

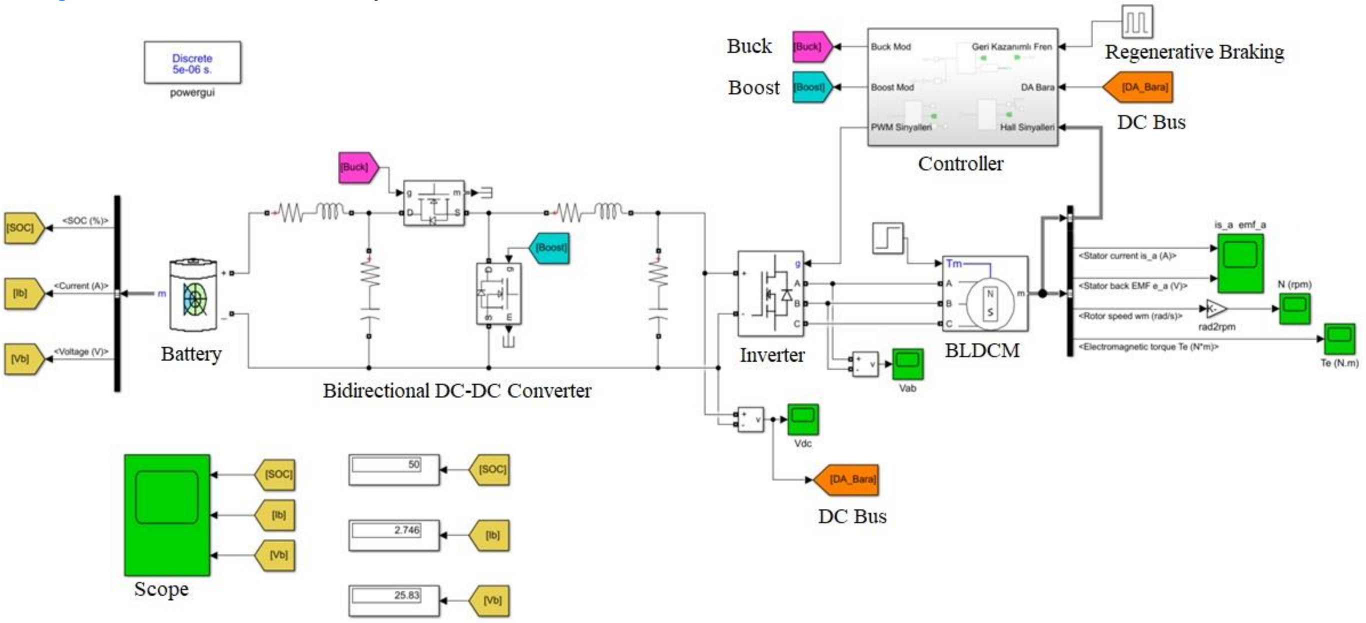

Figure 10. MATLAB/Simulink Model of The System

4. RESULTS OF SIMULATION

The external rotor BLDCM used in the proposed system can operate in the 24-36V range. A battery with a nominal voltage of 24 V is preferred as the supply of the scooter motor. The voltage induced in the rotor decreases as the motor slows down during regenerative braking. The decreasing voltage is increased above the battery voltage by the bidirectional converter working as an amplifier. However, the converter can increase this voltage up to a certain rate. The energy flow to the battery stops when this value is lower than the battery voltage. The DC voltage at the input of the inverter during braking is shown in Figure 11. The current flowing towards the battery is shown in Figure 12 with the increase of this voltage and the State of Charge (SOC) of the battery is shown in Figure 13.

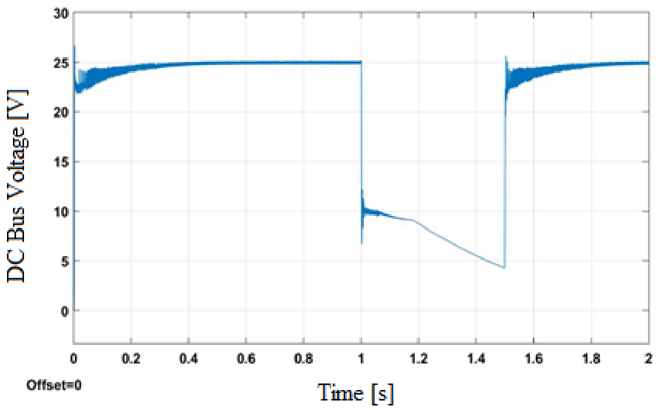

Figure 11. DC Bus Voltage of The Proposed System

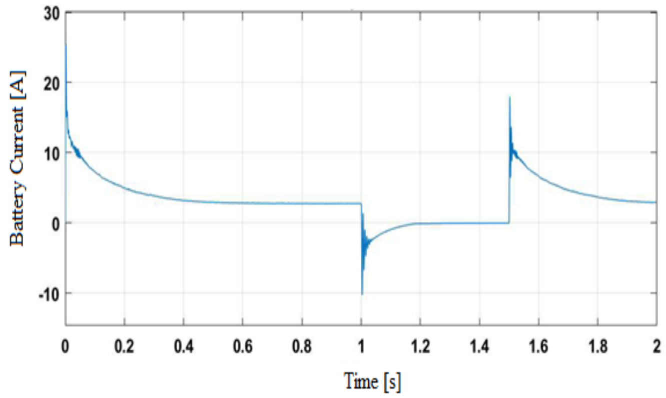

Figure 12. Battery Current of The Proposed System

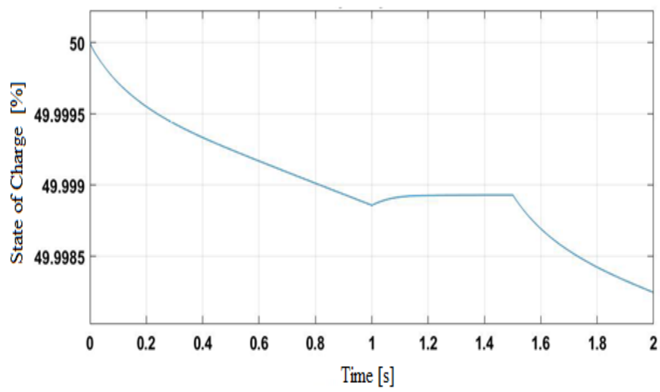

Figure 13. State of Charge of The Proposed System

Braking was applied between 1 and 1.5s as shown on the MATLAB/Simulink model. This is done to test bidirectional recovery. The generated brake signal is as in Figure 14.

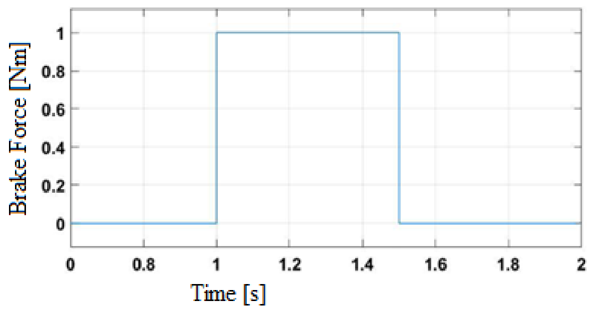

Figure 14. Brake Signal of The Proposed System

The change in BLDCM acceleration and braking is as in Figure 15.

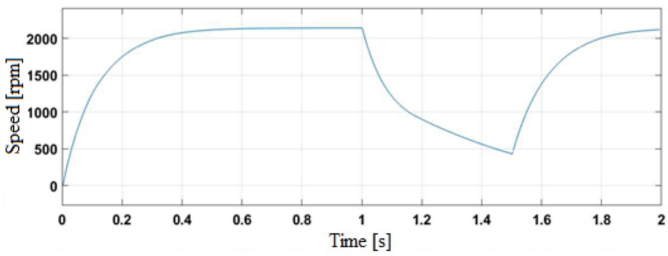

Figure 15. BLDCM Speed of The Proposed System

Figure 16 shows the electromagnetic torque of the BLDCM. It produces negative torque and the system tries to bring the torque production to zero as soon as the braking starts. When the stator current reaches zero, the electromagnetic torque is zero. It is seen that it starts to produce torque positive torque again with the end of braking.

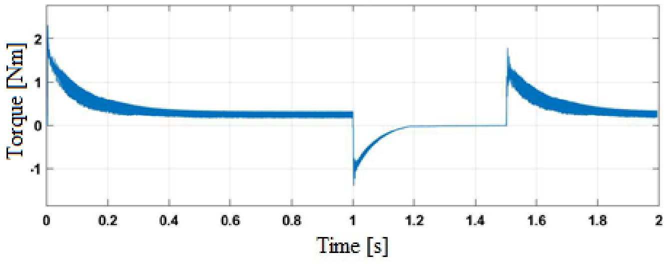

Figure 16. BLDCM Electromagnetic Torque

The BLDCM is decelerating with the brake signal. Accordingly, the back-EMF voltage induced in the motor windings will decrease. The transfer of the recovered energy to the battery is provided by increasing this voltage with a bidirectional DC-DC converter. Since the battery voltage cannot be reached after a certain voltage, the regenerative braking torque becomes zero. The back-EMF formed by the deceleration of the BLDCM is as in Figure 17.

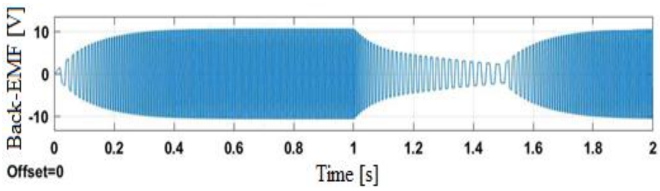

Figure 17. Back-EMF Curve of Phase A

Since the back-EMF is zero at the start of the BLDCM, the inrush current is high. The current curve of one of the phases of the BLDCM is as seen in Figure 18. Since the back-EMF voltage opposes the battery voltage, the stator current decreases with the increase of the back-EMF. During regenerative braking, since the phase-to-phase voltage is higher than the battery voltage, a higher amount of reverse current flows towards the battery. In this case, since the back-EMF will decrease with the deceleration of the BLDCM, the current flowing in the opposite direction will also decrease. The current becomes zero, when the DC bus voltage cannot be increased above the battery voltage.

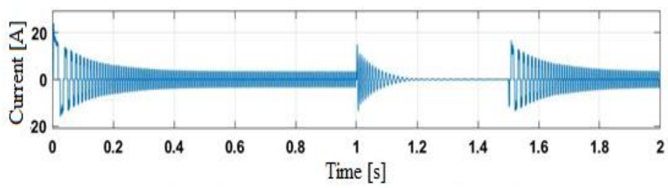

Figure 18. Current of Phase A

5. CONCLUSION

Scooters have become an integral part of life, especially in big cities. This transportation vehicle, which is in the class of light electric vehicles, has a very common use. The biggest problem with scooters is their short range. In this study, MATLAB/Simulink modeling of bidirectional DC-DC converter regenerative recovery circuit for scooter was carried out. The control algorithm required for BLDCM to operate in the regenerative braking region with regenerative recovery, which has not been given importance by scooter manufacturers and researchers, has been developed and the power electronic circuit has been modeled. The biggest benefit of this modeled system is that the battery is charged with the regenerative recovery circuit during braking, thereby increasing the range. Although the proposed model is realistic, it is necessary to ensure the accuracy of the work with the real road test. In this study, a recovery was achieved within the first 0.2s with braking within a 0.5s time interval applied to the system as a regenerative brake. At the first moment, a pulse current of 10A was produced, and during the braking period, this current was damped and reached zero. It is predicted that the production of the prototype of the proposed system will be higher, since more braking time will be exposed with realistic road testing. In the near future, it is thought that this model will be produced and the gains obtained by the real road test will be modeled. It will be investigated how much the recovery will affect the battery for different operating situations with the work to be done.

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BIOGRAPHIES

Ali Sinan ÇABUK was born in Denizli, Turkey on September 11th, 1976. He received the B.S., M.S. and Ph.D. degrees from the Marmara University in Istanbul, Turkey. He is currently an Associate Professor in Electrical Engineering Department at Istanbul Technical University in Istanbul, Turkey. He had been studying on his doctorate thesis from 2012 to 2013 at the Department of Electrical Machines, Drives and Automation, Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia. His research interests include electric machines and drives, electric vehicles, power electronic circuit design and simulation, mechatronic system design, automotive mechatronics, robotics, renewable energy and IoT systems.