A Bi-directional DC-DC Converter Fed DC and AC Motor for an Electric Vehicle

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***Abstract*—This letter paper proposes a bidirectional DC-DC converter-fed DC motor for an electric vehicle. The converter is designed to provide power flow in both directions, allowing the vehicle to charge its battery efficiently during regenerative braking and use the stored energy in the battery to power the motor during acceleration. The DC motor was chosen for its ease of use, dependability, and high torque output, making it ideal for use in electric vehicles. The proposed system can provide efficient and reliable power transfer in both directions, making it a promising solution for electric vehicle propulsion systems, according to simulation results.**

I. Introduction

As the demand for environmentally friendly transportation grows, electric vehicles (EVs) have emerged as a promising solution for reducing greenhouse gas emissions and reliance on fossil fuels. However, issues such as limited driving range and long charging times continue to stymie EV adoption. Researchers have been investigating various power electronics and motor drive technologies to improve the efficiency and performance of EVs in order to address these challenges. In EVs, one such technology is the use of bidirectional DC-DC converters. These converters allow power to flow in both directions between the battery and the motor, allowing the vehicle to charge its battery efficiently during regenerative braking and use the stored energy from the battery to power the motor during acceleration. Because of their simplicity, dependability, and high torque output, DC motors are also advantageous in EVs. We propose a bidirectional DC-DC converter-fed DC motor for an electric vehicle in this letter paper. We will describe the converter and motor's design and operation, as well as present simulation results to demonstrate the system's efficiency and reliability. We believe that the proposed system has the potential to address some of the issues associated with EVs while also contributing to the development of more environmentally friendly transportation options. [1]

II. Design Specifications

A. Problem Description

Despite their advantages in electric vehicles, DC motors face a number of challenges in terms of energy efficiency and performance optimization. The primary goal of this research is to create an effective power conversion system for DC motors in EVs that ensures optimal energy management and efficient motor control. The solution must support bidirectional power flow, energy recuperation during regenerative braking, and smooth and precise motor control. The use of unidirectional DC-DC converters for DC motor control in electric vehicles is currently a state-of-the-art solution. These converters can supply the necessary voltage and current to the motor, but they lack the bidirectional functionality required for energy recovery during regenerative braking. Furthermore, some of these solutions have efficiency, control complexity, and power density limitations. Several bidirectional DC-DC converter topologies, including isolated and non-isolated converters, have been proposed in the literature. However, due to their isolated nature or excessive switching losses, these topologies frequently suffer from issues such as high component count, complex control schemes, and limited efficiency. As a result, a novel bidirectional DC-DC converter design is required to overcome these limitations and provide efficient energy management and precise motor control for electric vehicles.In summary, the problem addressed in this paper is the development of a bidirectional DC-DC converter-fed DC motor for electric vehicles that can provide efficient energy management, energy recovery during regenerative braking, and smooth and precise motor control. This will entail investigating existing state-of-the-art solutions, identifying their shortcomings, and proposing a novel converter topology and control scheme to address these issues. [2]

B. Design Requirements

This design specification outlines the requirements and constraints for the development of a bidirectional DC-DC converter-fed DC motor for an electric vehicle. The converter should ensure efficient energy management, allow for energy recuperation during regenerative braking, and provide smooth and precise motor control. These are following concepts that will be implemented on the design model:

- DC motor subsystem: The model should include a subsystem representing the DC motor, with parameters such as motor resistance, inductance, and back EMF constant. The subsystem should simulate the motor's torque and speed characteristics.
- Bidirectional DC-DC subsystem: A subsystem representing the bidirectional DC-DC converter should be included in the model, along with parameters such as input voltage, output voltage, and switching frequency. The subsystem

should simulate the power flow, efficiency, and control capabilities of the converter.
- A battery system: A system representing the battery pack should be included in the model, with parameters such as battery voltage, capacity, and state of charge. During vehicle operation and regenerative braking, the subsystem should simulate the battery's charge and discharge characteristics.
- Inverter: The converter should be capable enough to alter the incoming Dc or Ac current
- Motor Controller subsystem: A subsystem representing the motor controller, which generates control signals for the bidirectional DC-DC converter, should be included in the model. To achieve precise motor control and energy management, the controller should use a control strategy such as PI, PID, or model predictive control.
- A measurement subsystem: A subsystem that measures the output and input parameters such as the state of charge after a certain period of time

III. Modelling and Simulation Results

A. Equations

Developing a Simulink model for a bidirectional DC-DC converter-fed DC motor for an electric vehicle necessitates the use of equations that describe the behavior and interactions of various system components. The following are brief explanations of some key equations used in the model:

- Duty Cycle: Duty Ratio determines the ratio of the duration of a signal's active (ON) and inactive (OFF) state. This ratio is usually referenced as a percentage.
- Inductor current: The maximum value of current going through the inductor during the duty cycle that we used. The formula for inductor current uses the source voltage, duty ratio and resistance in the circuit
- Rate of Change of Inductor Current: It shows the change in current values over a period of time. The formula for the rate of change of inductor current uses the source voltage, the duty ratio, the time period (inverse of switching frequency), and the value of the inductance.
- Minimum capacitance: It is the value of the minimum capacitance required in the DC-DC converter circuit for fundamental functioning. The formula for minimum capacitance uses the duty ratio, the resistance in the circuit, the switching frequency, and the ripple factor.
- DC Motor: The motor subsystem is modeled using the electrical and mechanical equations that govern DC motor operation. The electrical equation is given by the applied voltage (V), motor resistance (R), inductance (L), current (I), and back EMF (E)
- Battery Equation: The battery subsystem equations is given by the battery voltage (Vb), capacity (C), state of charge (SOC), and the charge and discharge current relationship (I)

Duty Ratio

$$D = \frac{V_0}{V_0 + V_s}$$

Inductor Current

$$I_L = \frac{V_s * D}{R(1-D)^2}$$

Rate of Change

$$\Delta I_L = \frac{V_s * D * T}{L}$$

Minimum Capacitance

$$C = \frac{D}{Rrf}$$

DC motor

$$V = RI + L(\frac{dI}{dT}) + E$$

Battery Equation

$$V_b = V_{oc} - Ri$$

Fig. 1. Eqautions used for the simulation model

B. Simulations

The model created on Simulink represents a regenerative braking scheme for electric vehicles driven by a permanent magnet synchronous motor (PMSM). The PMSM is used in this case rather than the DC motor to replicate the motor block used in large-scale electric vehicles in production today. Regeneration begins when the brake is pressed. When the brake is pressed, the amount of brake torque supplied is determined by the brake torque. The energy dissipated in the brakes is energy that can be harnessed to replenish the vehicle's battery.

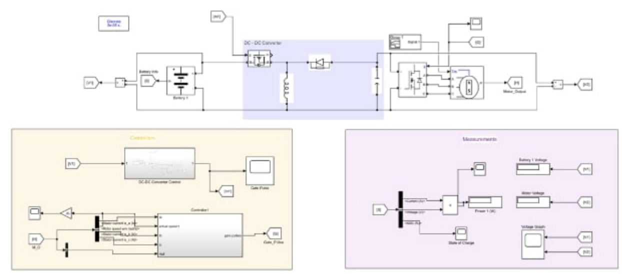

Fig. 2. Simulation Model

The simulation displays a traction chain as referenced before: the DC battery provides voltage to the DC-DC converter, which then feeds voltage to the inverter. The inverter converts the DC voltage to three-phase power that can be fed into the PMSM. During the recharging phase, the PMSM supplies power back into the traction chain in the opposite direction, through the DC-DC converter to power the battery. Each component in the traction chain will be described in detail below: DC Battery: The DC Battery used in this system is a 5V Lithium - Ion battery, with a rated capacity of 20 Ah. The initial state of charge is kept at 60 percent, and the battery's response time is kept at 30s. DC-DC converter: The DC-DC converter used in this system is the simplified buck-boost converter, with one MOSFET used as a switch. One capacitor and one inductor is used in the converter, and a diode is used to separate the two circuit loops. A gating sequence is used for the MOSFET switch, which takes the battery voltage as its input, and outputs a binary sequence that flips every second.

PMSM Motor: The PMSM motor implements three phases in its functioning, providing a trapezoidal back EMF waveform. The mechanical input for the motor is torque, which is provided using a signal builder. Universal Bridge: The

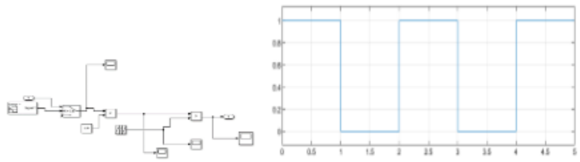

Fig. 3. Simulation Model for MOSFET Gate Sequence

universal bridge used in this system has three bridge arms and uses a MOSFET as its power electronic device. The gating sequence for the universal bridge takes in a variety of motor outputs as its input, (such as the three stator currents, the rotor speed and the hall effect currents) and outputs a gating sequence for the universal bridge. The gate controller consists of three sub-controllers: the speed controller, the hall effect decoder and the current controller. The speed controller applies the error between the reference and actual motor speeds to a PI controller for error correction. The hall effect decoder takes the hall effect current as its input and outputs the position of the magnet in the motor. The product of the speed controller and the hall effect decoder is then sent to the current controller, along with the stator currents. Using control logic and a set of relays, the output of the current controller is sent to the universal bridge as a gating sequence.

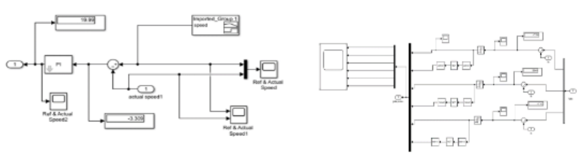

Fig. 4. Speed (left) and Current (right) Controller

The recharging process can be observed by examining the gate pulse of the DC-DC converter's MOSFET. During the ON state, the converter operates in buck mode, supplying voltage from the battery to the motor. In the OFF state, it switches to boost mode, utilizing the motor's back EMF. The recharging effects are visible in the voltage and state of charge graphs in Fig 5. Between 1-2 and 3-4 seconds, when the MOSFET is OFF, both voltage and state of charge increase rapidly. When the MOSFET is ON, the motor voltage mirrors the battery, and the state of charge declines linearly

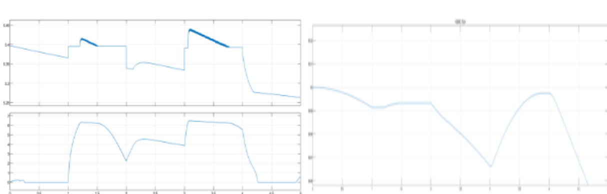

Fig. 5. Voltage Graph for Battery and Motor and the State of charge

The battery power is observed to increase during the MOSFET OFF phase. As shown in Fig. 6, during the time period of 1-2, the power appears to be negative. This negative power is due to the reverse polarity of the battery, indicating that the battery is receiving power from the energy converted by the regenerative braking system. Furthermore, from the time period of 2-3, when the motor is active, power is drawn from the battery and transferred to the motor, and this cycle repeats throughout the operation.

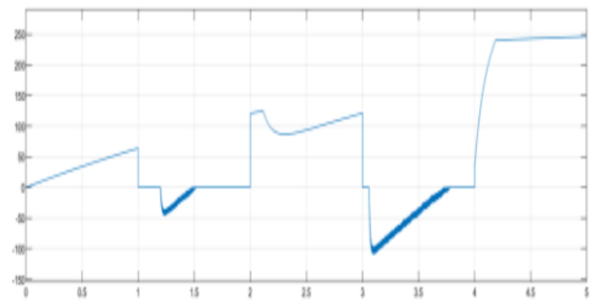

Fig. 6. Voltage Graph for Battery and Motor and the State of charge

IV. Prototype

The physical prototype consists of similar parts as outlined by the Simulink Simulation. In this case, the goal is to model a small EV. Therefore, the components include Arduino Uno, an External 9 V DC Power Source, a BuckBoost Converter (Input: 5.5 V - 30 V, Output: 0.5V - 30 V), an L298N DC Motor Driver Module consisting of dual H-bridges and MOSFET, a Permanent Magnet DC Motor (Input 12 - 24 V, Output: 3500 RPM Max) and a full wave bridge rectifier with capacitor load to mimic a battery holding charge.

The components are arranged in the following diagram to suit the needs of a small electric vehicle driving feature and a regenerative braking feature The circuit diagram allows the Arduino to communicate with the L298N motor driver to switch the MOSFET transistor to a specific duty cycle and implement various speeds. The buck-boost converter steps up the voltage from the external DC power supply to operate the L298N motor driver at 12 V. The L298N module has an internal 2-voltage drop so therefore the boost converter is supplying 14 V to accommodate the drop. The Arduino connects pins 5 and 4 on the L298N driver to control the DC motor polarity and drive the motor in a clockwise direction. Pin 3 is for pulse width modulation signals and therefore provides the motor module with the necessary commands. In one implementation, the Arduino is set to rise from 0 percent duty cycle to 100 percent and then back down to 0 percent in 20 ms increments. This is to show the varying speed and mimic a small EV taking off from rest to max speed and then back to rest. If this code was implemented with the necessary regenerative braking hardware infrastructure, back emf would be captured, rectified, and then boosted to charge the capacitor(battery mimicking) to hold a charge.

The regenerative charging is disabled as a proper flyback diode and the full wave rectifier was not properly implemented. However, the necessary infrastructure was available and the circuit design characteristics were calculated correctly. For improvement purposes, this implementation will be added if time permitted or for continuous improvement of the model.

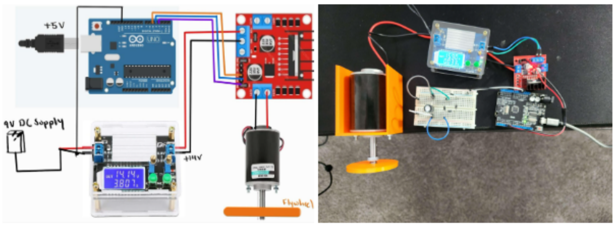

Fig. 7. Schematic diagram of a small EV physical prototype

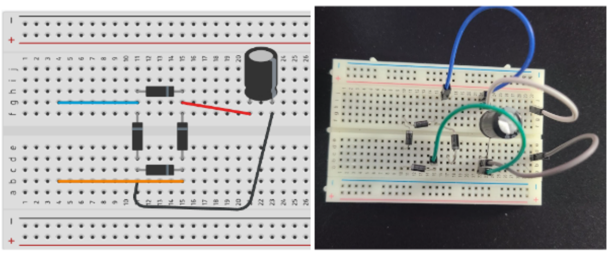

Fig. 8. Schematic for small EV regenerative charging module

V. Conclusion

In Conclusion, the creation of a Simulink model for a bidirectional DC-DC converter-fed DC motor for an electric vehicle provides a powerful tool for analyzing and optimizing the overall system performance. The model allows for comprehensive simulation and evaluation of the system's efficiency, motor control, and energy management under various operating conditions by incorporating equations and subsystems representing the motor, bidirectional converter, battery, and motor controller. Researchers, engineers, and designers can use the model to investigate the effects of various control strategies and parameters on system performance. Furthermore, it enables the simulation results to be validated against experimental data or benchmarked against other published models and literature. The model can also be used to perform sensitivity analysis, which identifies the most important factors influencing the overall performance of the bidirectional DC-DC converter and motor control. The physical prototype can be called a partial success as it incorporates all the design requirements for a bi-directional DC-Dc converter fed Dc motor for a small Electric vehicle. It can simulate driving and regenerative braking however, the hardware infrastructure is not integrated for regenerative braking. The output of the model matches the expected ranges of a small EV such as an electric scooter or longboard. Conclusively, the project is successfully completed and achieved satisfactory results and outputs. Improvements should and will be made going forward to truly refine this project.

References

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[2] R. M and j. Savier, "Bidirectional dc-dc converter fed bldc motor in electric vehicle," 02 2021, pp. 1–6.