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Enhanced Performance of Bidirectional DC-DC Converters for Electric Vehicle Systems

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ABSTRACT
This paper centers on the dynamic performance analysis of bidirectional DC-DC converters, utilizing both half bridge and cascade topology configurations. It explores their operation in two-quadrant scenarios, such as forward motoring and forward braking, incorporating dynamic braking techniques to enhance efficiency and control. Additionally, the study thoroughly examines torque versus angular speed graphs to clarify the converters' dynamic behavior under various operating conditions. Through comprehensive simulation and modeling, this work aims to offer valuable insights into optimizing bidirectional DC-DC converters for diverse energy conversion applications and to deepen the understanding of their dynamic torque-speed characteristics, particularly in electric vehicle (EV) applications

Keywords-DC–DC converter, Electric vehicle, Bidirectional Converter,Two-Quadrant mode, Regenerative braking

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I. INTRODUCTION

The global shift towards sustainable transportation has led to a significant increase in the relevance of electric cars, or EVs. Governments and customers alike are placing a higher priority on electric vehicles than conventional internal combustion engine automobiles as worries about climate change and air pollution rise. [1] Technological developments in batteries have increased the range and cost of electric vehicles, contributing to this change. Furthermore, as renewable energy sources like solar and wind power are becoming more affordable, EVs are becoming even more alluring because they leave less of a carbon impact while in use.

The effectiveness and performance of electric cars are greatly influenced by energy converters. [2][17] To power the vehicle's propulsion system, these converters must convert electrical energy from the battery into mechanical energy. By streamlining this conversion process, cutting-edge power electronics and motor technologies are increasing the overall efficiency and range of electric cars. Additionally, bidirectional energy flow is made possible by the integration of smart grid technology, which enables EVs to function as mobile energy storage units and support system stability during moments of high demand.

In order to increase the efficiency and range of contemporary electric vehicles, regenerative braking has become a crucial component which is shown in figure 1. During braking and deceleration, this technology enables cars to recover kinetic energy, which is then transformed back into electrical energy and stored in the battery for later use. The energy efficiency of electric cars is greatly increased by regenerative braking, which captures energy thatwould otherwise be lost as heat in conventional braking systems. [3] Because of this, EVs with

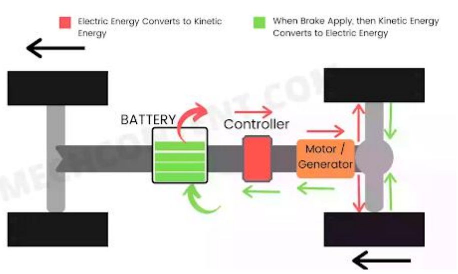

Fig 1: regenerative braking

regenerative braking systems have greater driving range and require less external charging infrastructure, which appeals to consumers looking for environmentally friendly modes of transportation even more. In urban driving situations, where there are lots of possibilities for energy recovery due to stop-and-go traffic, regenerative braking is very effective. Furthermore, regenerative braking systems may be easily combined with conventional friction brakes to provide reliable and smooth deceleration under a variety of driving conditions.

Even while regenerative braking has several advantages, its efficiency could differ based on a number of variables, including road conditions, battery level, and driving speed.However, regenerative braking is still a crucial component of electric cars' sustainability and energy efficiency, which adds to their allure as future ecologically beneficial modes of transportation.

DC output of renewable energy sources like solar or wind power and the AC grid in renewable energy systems. Control algorithms are used to manage the converter's voltage and current levels, resulting in effective power transmission and component protection. In order to maximize energy efficiency, increase system dependability, and enable sophisticated capabilities in contemporary power systems, these converters are necessary. classification of power electronic energy converters is shown in figure 2 below.

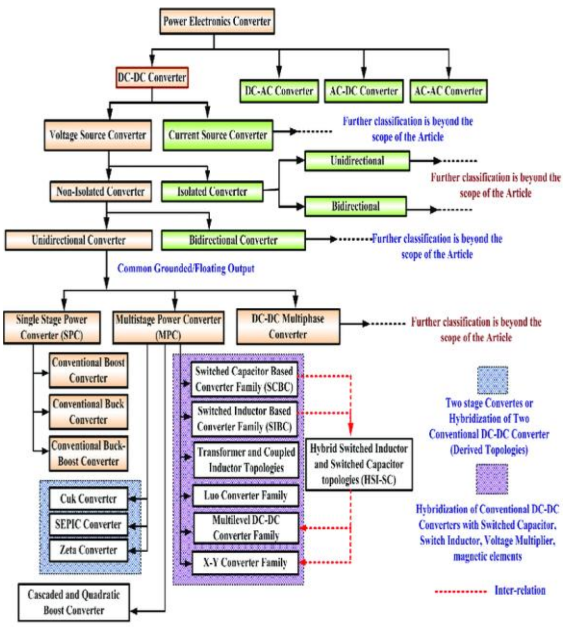

Fig 2: classification of energy converters

II. LITERATURE REVIEW

V. Viswanatha, A. C. Ramachandra and R. Venkata Siva Reddy, 2022 [4] have published an article that offers a thorough exploration of bidirectional DC-DC converter topologies and control algorithms, covering both transformer-based and transformer-less designs. It emphasizes the importance of efficient power flow management and identifies opportunities for future research, including the integration of artificial intelligence into control schemes.

Jiulong Wang, Bingquan Wang, Lei Zhang, Jianjun Wang, N.I. Shchurov,2022 [5] This paper introduces a novel approach for bidirectional interleaved DC/DC converters in battery-powered EVs, switching between boost and buck modes to save power and improve efficiency. It employs a buck-boost converter for voltage management during driving and braking. PI control stabilizes DC-link voltage in driving mode and reduces battery voltage fluctuations during braking. Current control maintains balanced battery current distribution. Simulation confirms its effectiveness in EV propulsion systems.

Erik Martinez-Vera, Pedro Bañuelos-Sánchez, 2024 [6] This paper offers a comprehensive review of bidirectional DC-DC converters and their control methods for Electric Vehicle (EV) applications. It proposes a classification based on the SAEJ1772 standard's three power rating levels. The comparison of circuit topologies includes factors like power rating, switching frequency, voltage gain, operating modes, component count, and power switch materials. It also discusses high switching-frequency topologies with emerging Wide Bandgap (WBG) devices

K. Suresh, Dr. R. Arulmozhiyal 2022 [7] This paper proposes a design and implementation of the bi-directional DC-DC converter for Wind Energy Conversion System. The proposed project consists of boost DC/DC converter, bi-directional DC/DC converter (BDC), permanent magnet DC generator and batteries. A DC-DC boost converter is interfaced with proposed wind system to step up the initial generator voltage and maintain constant output voltage.Muhammad Husnain Ashfaq, Jeyraj A/L Selvaraj and Nasrudin Abd Rahim 2021 [8] This paper reviews recent classical and supervisory control methods for bidirectional DC-DC converters.Renewable energy sources fluctuate with weather conditions, requiring stabilization with batteries. Bidirectional DC-DC converters link these sources with storage devices, adjusting voltage levels and managing power flow bidirectionally. Effective power flow control is crucial for system efficiency.

BoualamBenlahbib, Abedeljalil Dahbi, Bennaceur Fares, Abelkader Lakhdari, Noureddine Bouarroudj, Saad Mekhilef, Thameur Abdelkrim 2023 [9] This paper presents a bidirectional DC-DC buck-boost converter designed for PV system batteries, aiming to stabilize unpredictable renewable energy sources. It charges batteries during daylight in buck mode and enables battery discharge to power loads in boost mode when PV energy is unavailable. The converter manages power storage efficiently, with detailed design and implementation of the power and drive circuit boards. Experimental tests confirm its effectiveness and efficiency in charge and discharge modes, validating its reliability.

III. BIDIRECTIONAL DC-DC CONVERTERS

Bidirectional DC-DC converters are essential components in the field of power electronics that enable effective energy transfer between two DC voltage sources in a variety of applications. For efficient energy management and utilization, these converters permit bidirectional power flow, enabling energy exchange in both directions. [10] [13] Many topologies of bidirectional DC-DC converters have been developed for use in power electronics, each with unique benefits and applicability for certain uses. These topologies, which range from the adaptable buck-boost converter to the sturdy full-bridge converter and the effective dual-active bridge converter, represent a variety of design concepts and features.

3.1. Modelling of Half-Bridge Bidirectional converter using Dynamic Braking

A complex yet effective method of managing the bidirectional flow of electrical energy between two DC sources is the architecture of a half-bridge bidirectional DC-DC converter. In the field of power electronics, this design is a cornerstone because it provides a flexible platform that can efficiently and reliably facilitate bidirectional power flow while stepping up or down voltages. Sophisticated control method that coordinates the semiconductor switch flipping with input and output voltage and current monitoring from sensors governs the half-bridge bidirectional DC-DC converter's functioning. This control system maintains the optimum output voltage and current levels by dynamically varying the duty cycle of the switches, so guaranteeing optimal performance and efficiency.

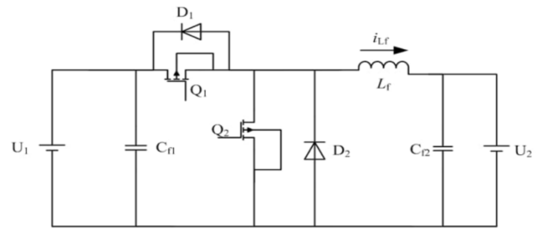

Fig 3: half bridge bidirectional dc-dc converter

The topology of the half-bridge bidirectional DC-DC converter embodies a synthesis of advanced semiconductor technology, sophisticated control algorithms, and innovative design principles [11] [14] [15]. As a versatile and efficient solution for managing energy flow bidirectional between DC sources, it plays a pivotal role in driving innovation and sustainability across diverse applications and industries, paving the way for the advancement of modern power electronic systems. The Half Bridge Bidirectional Dc-Dc Converter shown in figure 3.

3.2. Modelling of Cascaded Bidirectional converter using Dynamic Braking

A complex way to control the bidirectional flow of energy between several DC sources or energy storage components is through the architecture of a cascaded bidirectional DC-DC converter. This architecture provides increased flexibility, scalability, and efficiency in power conversion applications by combining many stages of bidirectional DC-DC converters cascaded together.[12] A bidirectional DC-DC converter architecture, such as a full-bridge or half-bridge arrangement, is usually coupled to form a cascaded structure at each step of the cascaded converter. The converter can manage greater voltage differentials or power levels thanks to the cascaded layout, which divides the voltage conversion over several stages while retaining the possibility for bidirectional energy flow.

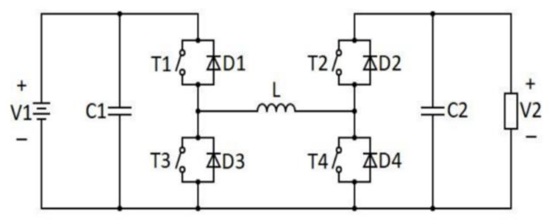

Fig4: topology of bidirectional cascaded converter

An advanced power electronics solution that can effectively manage energy flow bidirectional between numerous DC sources or energy storage units is a cascaded bidirectional DC-DC converter. [16][18] With this design, power conversion applications can benefit from increased flexibility, scalability, and efficiency since bidirectional converters are stacked in several stages. The cascaded converter adapts to changing voltage needs and load situations by operating in several modes to either power the output load or charge the input source in various scenarios.

IV. SIMULATION

4.1. Half Bridge Converter with dynamic braking

The goal is to use MATLAB Simulink to develop dynamic braking for reverse power flow in a bidirectional DC-DC half bridge converter. In contemporary power systems, bidirectional converters are essential for the effective transmission of energy between various voltage levels. The converter can efficiently waste surplus energy and regulate the direction of power flow by using dynamic braking. This allows the converter to absorb power from the load and return it to the source as needed.

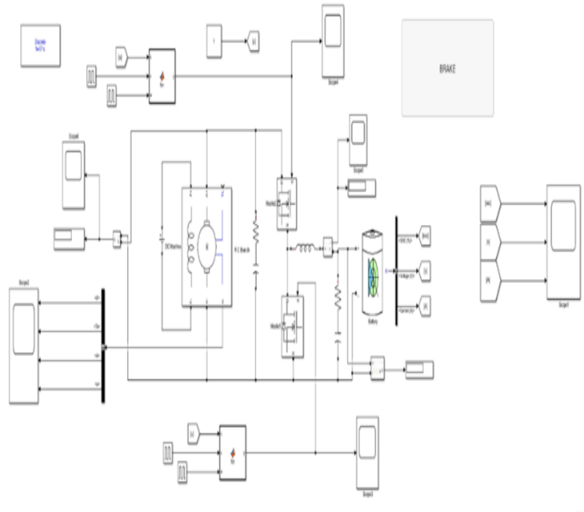

Fig 5: Simulink Model of Half Bridge Converter with dynamic braking

4.2. Cascaded Bidirectional converter using Dynamic Braking

A cascaded bidirectional DC-DC converter represents an advanced power electronics solution capable of efficiently managing energy flow bidirectional between multiple DC sources or energy storage elements. This topology consists of multiple stages of bidirectional converters cascaded together, offering enhanced flexibility, scalability, and efficiency in power conversion applications. In various scenarios, the cascaded converter operates in different modes to either power the output load or charge the input source, adapting to varying voltage requirements and load conditions.

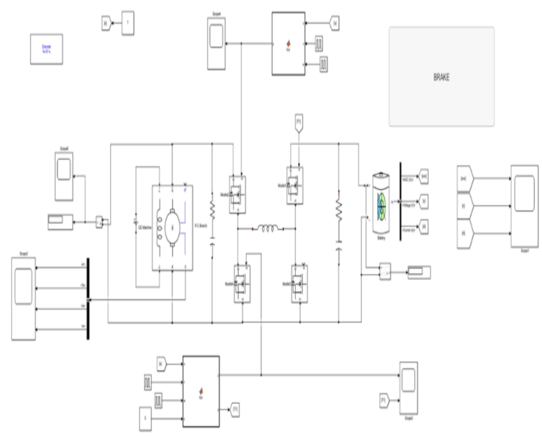

Fig 6: Simulink Model of Cascaded Bidirectional converter using Dynamic Braking

4.3. Transition Logic

The transition between motoring and braking modes is governed by the activation of the brake button. When the brake button is pressed, the flag variable changes from 1 to -1, triggering the transition to braking mode. Subsequently, the PWM signals are adjusted to switch the MOSFET operation accordingly, ensuring seamless mode transition.

Fig 7: Brake (Push button)

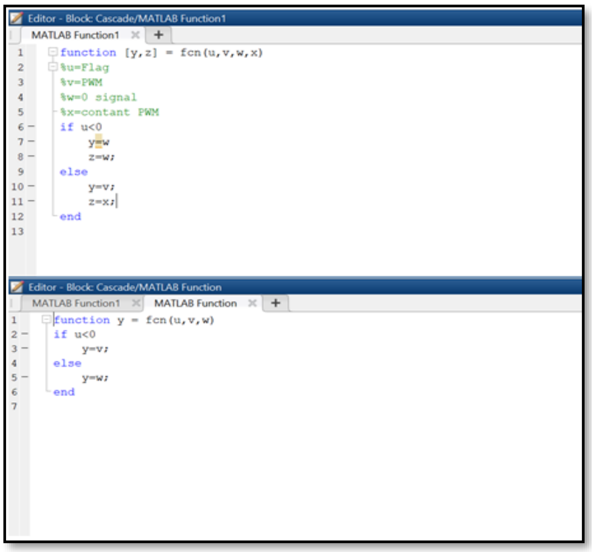

Fig 8: MATLAB code defines the transition logic and controls the generation of PWM signals for MOSFET switching.

V. RESULTS AND DISCUSSION

5.1 Pulse Waveforms

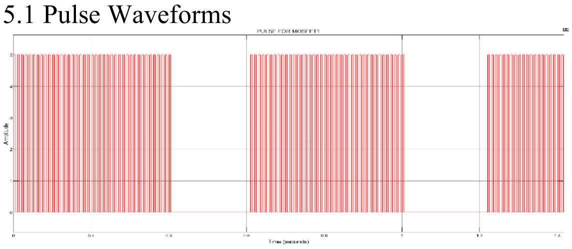

Fig 9:Pulses for monitoring

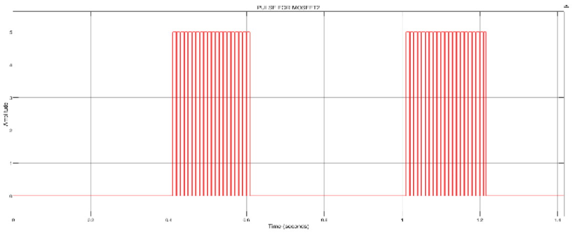

Fig 10:Pulses during dynamic braking

5.2 State of Charge

The graph that displays a battery's state of charge (SoC) in both forward driving and stopping modes shows how energy flow is dynamically interplayed. The SoC gradually drops during forward driving as the batteries discharge to power the motor, indicating the exhaustion of stored energy. On the other hand, while the motor is operating in forward braking mode, the excess energy it produces is absorbed by the battery, which increases the SoC. This variation in SoC emphasises how energy is transferred both ways inside the system, which is necessary for effective management and use of battery resources across a range of operating modes.

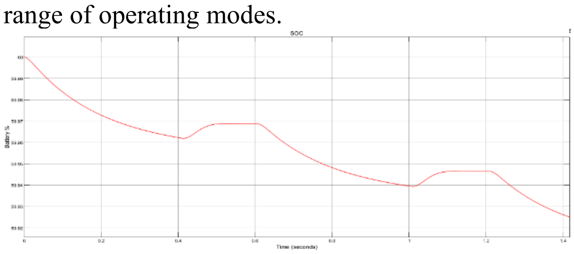

Fig 11:SOC of Half-Bridge converter during forward motoring and braking modes

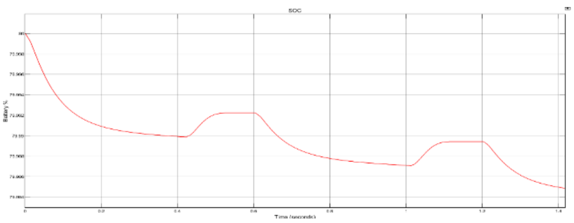

Fig 12:SOC of Cascaded converter during forward motoring and braking modes

5.3 Battery Voltage

When considering the battery's voltage dynamics in the forward driving and braking modes, a unique pattern that reflects the fluctuating energy flows and demands is shown. The voltage progressively drops during forward driving as the battery empties, reflecting the decrease in stored energy that is available to power the motor. On the other hand, while energy is being added to the battery in the forward braking mode, the voltage increases as the battery absorbs the excess energy coming from the motor. This voltage variation is a vital sign of the battery's condition and the equilibrium between the system's energy use and regeneration, both of which are necessary to sustain performance and operating efficiency.

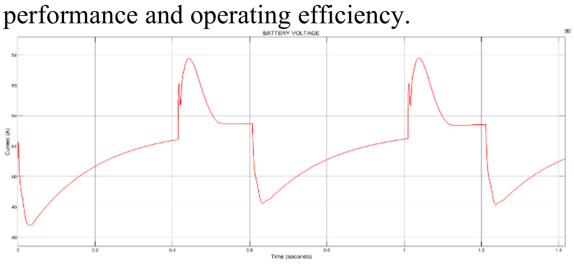

Fig 13: Battery voltage in Half Bridge during forward motoring and brakingmodes

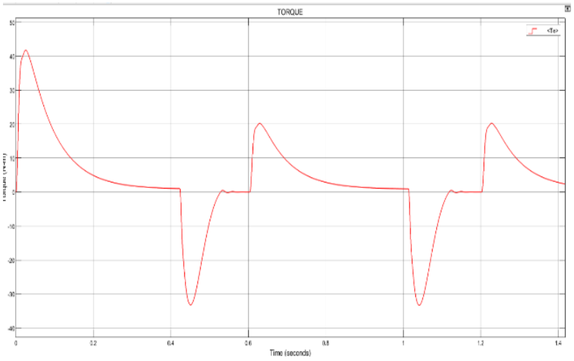

Fig 14: Battery voltage in Cascade converter during forward motoring and brakingmodes

5.4 Motor Speed

Angular speed is crucial in defining the rotational motion of the motor and the resulting impacts on the movement of the vehicle when it comes to forward motoring and stopping modes. When driving forward, the motor's rotational speed determines how quickly it spins in order to produce torque and move the car forward. The throttle input and load conditions are two examples of elements that affect this angular speed fluctuation, which affects the vehicle's acceleration and speed. On the other hand, when the motor is in forward braking mode, it changes its angular speed from propelling to generating. Here, the motor produces torque in the opposite direction to slow down the vehicle and facilitate energy transfer back into the battery, causing the angular speed to drop. As a result, angular speed is a crucial factor in controlling the system's dynamic interaction between propulsion and regeneration, which affects vehicle economy and performance.

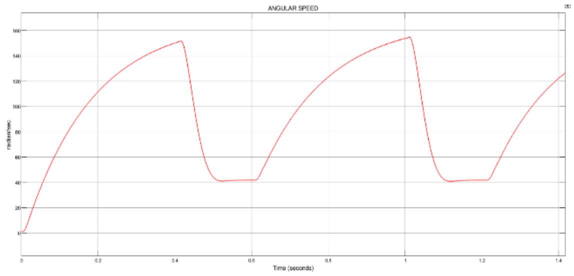

Fig 15:Motor Speed in Half Bridge during forward motoring and brakingmodes

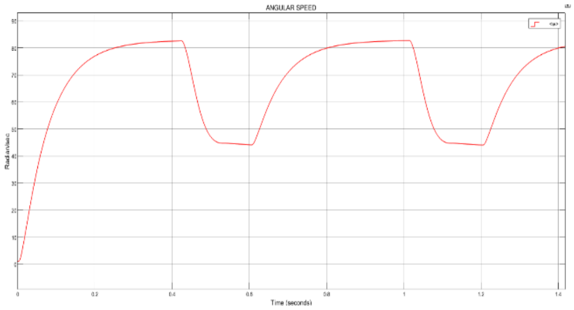

Fig 16:Motor Speed in Cascade converter during forward motoring and brakingmodes

5.5 Motor Armature Voltage or Converter Output Voltage

When considering the battery's voltage dynamics in the forward driving and braking modes, a unique pattern that reflects the fluctuating energy flows and demands is shown. The voltage progressively drops during forward driving as the battery empties, reflecting the decrease in stored energy that is available to power the motor.

On the other hand, while energy is being added to the battery in the forward braking mode, the voltage increases as the battery absorbs the excess energy coming from the motor. This voltage variation is a vital sign of the battery's condition and the equilibrium between the system's energy use and regeneration, both of which are necessary to sustain performance and operating efficiency.

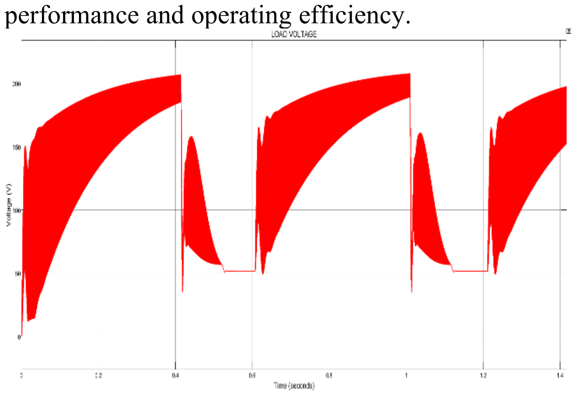

Fig 17: Load voltage in Half bridge converter

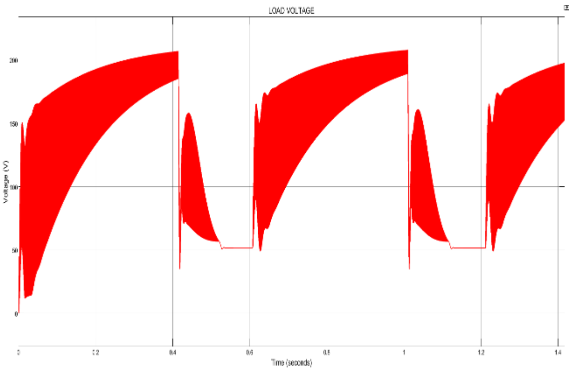

Fig 18: Load voltage in Cascade converter

5.6 Motor Torque

Torque is produced by the motor as it propels the vehicle forward. According on the vehicle's weight and speed, this torque varies. However, the motor changes into generator mode and shifts gears when the car has to slow down. It now generates torque in the opposite direction to slow the car down and returns some of that energy to the battery, rather than pushing it ahead. Thus, the motor operates differently depending on whether the vehicle is driving or halting, which has an impact on the force it produces

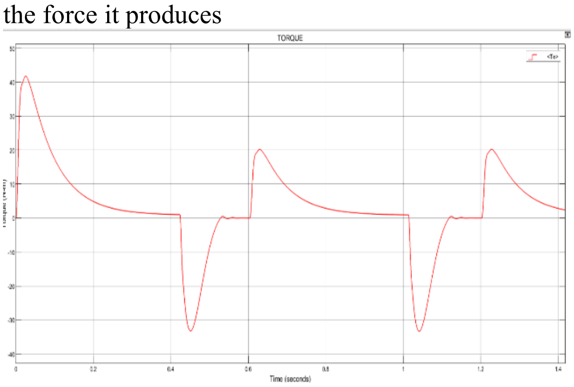

Fig 19: Torque vs time graph of Half-bridge converter

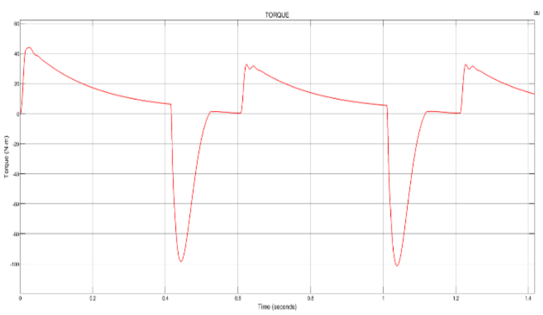

Fig 20: Torque vs time graph of Cascaded converter

5.7 Observations

a. Half bridge converter

S.No	Parameters	Forward Motoring Mode	Forward Braking Mode
1	Battery SOC	Decreases from 80% to 79.95%	Increases from 79.955% to 79.962%.
2	Battery Voltage	Decreases from 49.53 V to 48.67 V	Increases from 51.77V to 51.90V.
3	Motor Speed (rad/sec)	162.3 rad/sec at 1.2sec	Decreases from 162.3 rad/sec to 42 rad/sec.
4	Motor Armature Voltage	Increases to 202.8Volts Vmin=199.8V, Vmax=205.8V $\Delta V = 6V$	Decreases from 205.8 V to 51.9 V.
5	Motor Torque (N-m)	1.659N-m (No load)	Increases negatively and gradually decreases to zero.

b. Cascade Converter

S.No	Parameters	Forward Motoring Mode	Forward Braking Mode
1	Battery SOC	Decreases from 80% to 79.95%	Increases from 79.955% to 79.963%.
2	Battery Voltage	Decreases from 50.58 V to 49.32	Increases from 51.76A to

		V	51.91A.
3	Motor Speed (rad/sec)	160.1 rad/sec at 1.2sec	Decreases from 160.1 rad/sec to 40 rad/sec.
4	Motor Armature Voltage (Converter o/p voltage)	Increases to 200 Volts V_{min}=198V V_{max}=203.8 V $\Delta V = 5.8V$	Decreases from 200 V to 50 V.
5	Motor Torque (N-m)	1.756N-m (No load)	Increases negatively and gradually decreases to zero.

VI. CONCLUSION AND FUTURE SCOPE

This work focuses on dynamic braking in forward driving and forward braking modes, thoroughly examining the modelling and analysis of bidirectional DC-DC converters in both half bridge and cascaded topologies. It has been shown via extensive research and modelling that these converters effectively control power flow in both directions while maintaining peak performance throughout driving and braking activities.

The results not only advance knowledge of bidirectional DC-DC converters but also provide light on real-world uses for them in a number of industries, including industrial automation, renewable energy systems, and electric cars. The paper also emphasises how important dynamic braking systems are for improving system dependability and energy economy. All things considered, this study offers insightful information and possible directions for further investigation and advancement in the field of energy conversion systems and power electronics.

This work has promising opportunities in several important areas going future. By applying optimisation approaches, we may try to increase the flexibility and efficiency of bidirectional DC-DC converters. Additionally, we may create new methods of controlling them to improve their performance in various scenarios. These converters might provide smoother grid integration and improved energy management when connected to energy storage systems. Investigating rapid problem detection and resolution can increase the dependability of these systems. Lastly, putting these concepts to the test in practical settings can help make them applicable to sectors like renewable energy and electric car manufacturing.

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