Bi-Directional DC-DC Converter for Enhanced Power Management in Electric Vehicle Applications

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Bi-directional DC-DC Converter for Enhanced Power Management in Electric Vehicle Applications

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***Abstract—The* increasing adoption of electric vehicles (EVs) as a sustainable and efficient alternative to conventional gasoline-powered vehicles highlights the critical need for a reliable and effective charging infrastructure. This paper introduces an advanced control strategy for a power-split hybrid transmission system, which integrates a bi-directional DC-DC converter to optimize power management in hybrid and electric vehicle applications. The system architecture, incorporating a planetary gear system alongside motor and generator components, functions as a variable ratio gear, enabling smooth and efficient energy distribution. MATLAB/Simulink simulations assessed the system's performance under acceleration and regenerative braking conditions, highlighting the converter's ability to manage energy flow effectively between the battery and motor. The research investigates the differences between isolated and non-isolated DC-DC converters, highlighting the benefits of both designs in a variety of applications. Isolated converters improve safety and noise isolation; however, non-isolated systems are more compact and cost-effective. The results demonstrate the proposed system's ability to utilize electrical power exclusively during vehicle maneuvers, optimize energy efficiency, and reduce reliance on mechanical power. This research underscores the potential for advanced DC-DC converter topologies to enhance power management strategies in hybrid systems, providing valuable insights for future innovations in energy storage, power conversion, and electric vehicle technologies.**

Keywords—Electric Vehicles, DC-DC, converters, Hybrid and Electric Vehicle Applications, Battery.

I. INTRODUCTION

In recent years, there's been a rising interest in electric cars because the global production of oil and gases is depleting. Electric vehicles (EVs) are typically classified into three main categories based on their power systems: some of the subcategories we have Hybrid Electric Vehicles (HEVs), Battery Electric Vehicles (BEVs), and Plug-in Hybrid Electric Vehicles (PHEVs). HEVs integrate the internal combustion engine and electric motor; regenerative braking and internal combustion engine to recharge battery-superior fuel efficiency- no external charging. BEVs have zero-emission electric drivetrains which means they are solely operated by rechargeable batteries which are filled from outside. This car combines both mechanisms, the benefits of which are obvious: PHEVs are designed to run on electricity up to a certain distance, and then can turn on an internal combustion engine in case of longer travel and it can also be charged from the outside. All these classifications depict various ways of cutting emissions and increasing efficiency in transportation technologies. On the other hand, BEVs and PHEVs can be charged via a power outlet and are normally provided with higher battery pack capacities [1]. When it comes to recharging electric vehicle batteries, two primary options are available: from the traditional electrical network power or through renewable energy resources.

However, in most of these countries, power fluctuations often cause frequent power interruptions, making grid charging unreliable. Consequently, stress has been directed towards the application of renewable energy like photovoltaic (PV) and fuel cell (FC) technologies. To efficiently utilize the DC voltage generated by these renewable sources, DC-DC converters and charger controllers are deployed in managing the flow of electricity, optimize battery performance and lifespan, and ensure safe charging operations [2] DC-DC converters are electronic devices employed to convert one level of DC voltage to another, typically to provide efficient power conversion in various applications [3]. Different types of DC-DC converters have been developed to meet specific requirements. DC-DC converters operate based on the principles of energy storage and switching [4]. They typically consist of switches (such as transistors), inductors, capacitors, and diodes, which work together to transform the input DC voltage to the desired output voltage level. Isolated DC-DC converters incorporate a physical isolation barrier, which offers improved safety, prevents ground loop issues, and provides benefits such as voltage regulation and noise isolation. These features make isolated converters ideal for applications where electrical isolation is crucial.

In contrast, non-isolated DC-DC converters do not include this isolation barrier, resulting in a more compact, cost-effective, and efficient design. Such converters are typically chosen for applications where space is limited, cost efficiency is important, and electrical isolation is not a primary concern [6]. Figure 1 provides a detailed overview of the different types of DC-DC converters, outlining their advantages and common use cases [7].

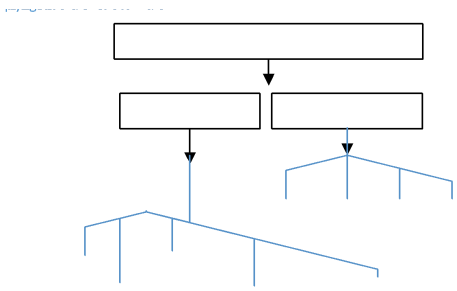

Fig. 1. Isolated and Non-Isolated DC-DC converters

These converters have a distinct importance in forming a direct current connection between the battery and inverter in the EVs. The paper focuses on power electronics converters and their role in the operation of EVs; BMS, converters, and motors are discussed in detail along with progress and issues in EV power conversion. In addition, non-isolated DC-DC converters introduce flexible and convenient solutions of DC-DC conversion for different power demands [8]. Some attempts have been made in improving the performance of the DC-DC converter: Ultra-step-up converters with low switch stress have been developed with the intention of improving the efficiency [9]. Furthermore, sufficient effort has been made to enhance the sizing and efficiency of DC-DC converters when connected with fuel cell stacks for powering loads [10]. However, much attention has been paid to power system that involve the sizing and performance of DC-DC converters interfaced with fuel cell stacks for providing DC loads, highlighting on more emphasis on off-the-shelf DC-DC converters used in specific applications [10].

In reference [11], more information on isolated DC-DC converters is given together with a more detailed class-A analysis of several converters; the flyback, forward, push-pull, full-bridge and half-bridge converters are discussed. Furthermore, Figure 1 presents the non-isolated converters, including the buck, boost, buck-boost, Cuk, and Single-Ended Primary Inductor Converter (SEPIC). This paper provides a comprehensive understanding to the working principles, benefits, and use of isolated and non-isolated converter topologies and their importance in today's power electronics for various applications, including distributed generation, renewables, and electric vehicles. It also shows the size of each converter and the difference in its performance to enable the determination of the most appropriate topology for a system with certain characteristics. An electrical isolation between the input and the output stands as the typical characteristic of isolated systems and ensures higher levels of safety and noise rejection. However, there is much higher usage of non-isolated converters as these converters have simple structure, easy to control, cheaper and compact size, thus it is well suited for low power applications. Many papers have investigated several types of DC-DC converter topologies as a major characteristic for electric vehicle (EV) applications, concentrating on efficacy and effectiveness [12]. The choice of a DC-DC converter influences the overall efficiency of an EV along with its size, mass and cost [12]. For instance, a boost converter is more appropriate for a circumstance that needs a high voltage while a buck converter should be appropriate for a circumstance that needs a low voltage [13]. For renewable power systems, non-isolated DC-DC converters are useful in stabilizing fluctuating DC output from generators such as photovoltaic and wind power system [14]. There are several types of these converters for instance the buck, boost, buck-boost, Cuk, and SEPIC and their principles together with their strengths and weaknesses especially for RE systems and for given applications have been discussed [14]. Furthermore, simulation data and results from several other works are discussed to justify the overall theoretical integration of DC-DC converters for efficiency in electric vehicle systems.

These converters, shown in Fig.2 are buck-boost converters, which work in a way that they can provide a voltage output either higher than or lower than the voltage across the input, this makes it very useful in applications where the input voltage may vary greatly such as in battery driven systems. Further studies are conducted in development of buck boost converters especially in the quest to make photovoltaic (PV) energy generation systems with high efficiency. Hence, engineers are looking for possible methods of increasing the voltage gain of non-isolated DC-DC converters with new types of converters including SEPIC, Cuk, Lou, and Z-source converters based on the buck boost converter [17].

In electric vehicle applications, buck-boost converters are being explored for power management in interleaved bi-directional converter control systems [18]. This system is designed to protect the batteries from exposure to high peak currents, further enhancing the performance and longevity of the power storage system. The output voltage of a buck-boost converter is expressed as:

$$V_{out} = \frac{D}{1-D} * V_{in}$$

Where V_{in} is the input voltage, D duty cycle, and V_{out} output voltage.

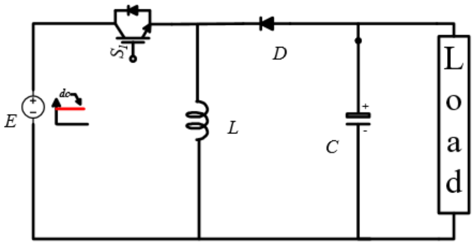

Fig. 2. Buck boost converter

II. LITERATURE REVIEW

For EVs to be efficient, the DC converter and charge controller are two important components that are indispensable. The DC Converter plays the major role in the energy conversion where direct current which is obtained from battery is converted into alternating current that is utility for running the electric motor. At the same time, it controls the voltage levels to reduce effects on the motors and to better perform and increase efficiency. At the same time, the charge controller regulate the charging process, protects the batteries from overcharging, increase the charging rates as well as constantly control the battery status. According to research [19], these components offer collective beneficial effects on the stabilization of the power of electric vehicles, productivity, and durability that are central to the evolution of enduring general transportation. In electric vehicles (EVs), we have the necessity of several voltage levels from the high voltage battery pack for the electric motor, onboard electronics, and auxiliary loads: the DC-DC converters play a crucial role in this aspect. These converters are generally classified into two main types: For single-port operations, there are benefits and risks as well as opportunities and challenges related to multi-port operations. However, both types are fast response and highly efficient with reliable performances [20], [21], and [22].

Thus, in a comparison of multi-port DC converters with single-port DC converters for EVs, it is necessary to compare the power management schemes and topologies. Multi-port converters are indispensable to the process because they define a common DC link circuit that connects various input power sources and drives both DC and AC loads using the DC input only. Besides that, multi-port designs do not require additional conversion stages because both DC-DC and DC-AC transformers can be integrated into one connection. These features make multi-port converters highly suitable for applications as dc micro grids and electric vehicles. Single Port DC converters are rather different as they generally move energy from an input port to an output port. While multi-device converters, can handle power flow from multiple input ports to a single output port, thus making them a Multi-Input Single-Output (MISO) converter [23]. Non-isolated converters for a multi-port DC-DC converter suitable for versatile power control of EVs, are distinguished into MISO, SIMO, and MIMO converters. MISO converters enable various forms of energy, for example, solar cells, or fuel cells, to be connected to one output, which is best for hybrid systems in which the different sources work together to power the EVs main drive. Meanwhile, SIMO converters take power from a single power supply and divide it out to multiple voltage levels to power up different branches of the connected EV, where these voltage levels may differ from subsystem to subsystem, such as an on-board charger and other auxiliary systems. MIMO converters include these functions and handle multiple inputs and outputs switching on and providing and consuming power [24]. These flexibility features in the selection of multi-port converter topologies make it easy to route energy efficiently, control power distribution, and improve EV performance, given the versatility of power sources and systems that may be interfaced in real time [28].

The study presents a new topology of a segregated DC-DC converter which applies fuel cells and batteries as input sources allowing power flow from the sources to the load and from the load to the battery during energy recuperation. This method work involved the analysis of different multiport converter to study their different topological categories and architectures and compare isolated and non-isolated structures in terms of their performance in different operating conditions as is presented in [12] and [14]. The study also discussed different optimizing methods for controlling multiport converter including ways to improve its efficiency and performance. Among the techniques that were discussed include the standard interleaved and cascaded boost converters which can be applied to boost converter systems and for gaining high voltages in multiport converter systems. Through exploring these strategies, the study also provides guidelines for selecting proper circuit configurations for enhancing power transfer capability and adapting to multiple power supply circumstances in electric vehicles and renewable energy MG applications.

However, as introduced in [16], these advanced topologies require additional costs and control complexity that are well-known for the design and implementation challenges. The paper also describes the drawbacks of traditional sources of DC-DC converters such as Boost, Buck, Buck-Boost, CUK, SEPIC and ZETA converters where such designs require a high number of components to achieve the desired performance characteristics. This has not only resulted in an increase in general price but also in reliability and compactness characteristics of such configurations, making such an approach less suitable for cost-sensitive or compact applications. Hence, to overcome such challenges, there is a need to design multiport converters with less bulky and elaborate structures but that have enhanced high operating efficiency and power density all the same but less demanding components and control circuitry. Moreover, the study introduces a low-gain multiport converter based on a topology from the switched-resonator converter (SwRC) family, which operates without a transformer and maintains a common ground across all ports.

Finally, the study [18] concluded that multiport converters have the potential to address various challenges in renewable energy integration, energy management, and system efficiency, paving the way for further advancements and applications in the field.

Another study in [19] supported the use of multiport DC-DC converter for renewable energy applications in an aim of improving system reliability through the hybridization of renewable energy sources. Their methodology involved the use of multi-input converters to achieve high step-up capability and continuous input current. The testing scenario includes considerations for voltage and capacitor size, as well as controlling battery discharging power through duty cycles. The findings indicate the proposal of a high step-up multi-input converter with a high-output voltage gain, essential for hybridizing fuel cells and battery systems. The challenges faced include the need for a converter with multi-input and high step-up capability, addressing discontinuous input current, and low voltage conversion gain.

Multiport converters have gained significant attention in the field of power electronics due to their numerous advantages over traditional single-input single-output converters. These benefits include simplifying system architecture, reducing the number of power converters required, lowering system costs, reducing size, improving overall system efficiency, providing improved power quality, better control over power flow, and enhanced fault tolerance [20]. The various topologies of multiport converters, such as full-bridge, half-bridge, and interleaved configurations, offer different advantages and trade-offs in terms of cost, efficiency, power density, and complexity [22]. The choice of topology for a multiport converter depends on specific application requirements and system constraints [21], [23]. Figure 3 shows how multiport converters, are important in handling and interconnecting of multiple power sources and loads present in today’s power systems [24]. Furthermore, multiport converters play an important role in the development of sustainable and intelligent power systems as part of a path to higher quality, reliability, performance, and green power distribution. In this respect, the given abilities allow managing inputs and outputs of various power resources and contribute to their efficient use with minimum waste levels in today's complicated power networks.

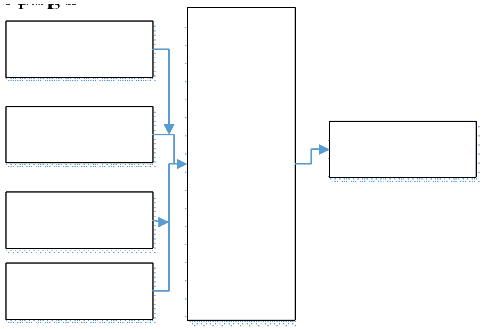

Fig. 3. Multiport concept employment in DC-DC CONVERTERS

The control of multiport converters is crucial for efficient and reliable operation. Advanced control methods like (PWM), sliding mode control (SMC), and model predictive control (MPC), are commonly employed to regulate the power flow and ensure stable operation of the converter under various operating conditions. Overall, multiport converters play an important role in combining and controlling different power sources and loads in modern power grids. They enable efficient power conversion, increase system flexibility, and aid in the creation of sustainable and smart energy systems. The ongoing research and improvements in multiport converter techniques aim to significantly increase their performance, efficiency, and usability in diverse power system applications. In [12], a multiport design employing a DC-DC converter for powering an electric automobile was described with a topology that contains three toggle switches that are IGBTs, two energies that are a battery and photovoltaic cells, and some additional components such as diodes, inductors, capacitors, and resistors. Charge controllers, often referred to as charge regulators or battery regulators, play an important role in green energy systems, particularly photovoltaic (PV) applications. Their primary function is to manage the charging process of batteries connected to the PV system, ensuring both efficiency and safety. Charge controllers are designed to prevent overcharging and deep discharging of batteries, which can significantly impact battery health. They continuously monitor the state of charge (SOC) of the batteries and the incoming power from the PV panel, adjusting the charging current and voltage to keep the batteries within their safe operating limits. Overcharging is a leading cause of battery explosions or damage, resulting in reduced battery lifespan and safety risks. Conversely, over-discharging can cause irreversible harm to battery health, diminishing their capacity. By monitoring voltage and current levels, charge controllers regulate the charging process to ensure batteries remain within their safe operating parameters [17].

A DC-DC converter is recognized as a non-ideal technology that suffers from several drawbacks; consequently, while evaluating the MPPT algorithm to maximize the energy production from solar installation between the PV system and the DC-DC converter. MPPT's main objective is to allocate the very specific point where voltage and current are at peak value (Vmpp) and (Impp) producing the highest power output (Pmpp). Solar panels can be majorly affected by temperature and weather conditions, utilizing MPPT will ensure the system operating at maximum efficiency under any circumstances [37]. Recently, a vast array of Maximum Power Point Tracking (MPPT) algorithms and designs have been developed, each with its own unique specifications, limitations, and practical applications. Due to the diversity of these approaches, no single, standardized classification system exists for MPPT algorithms. However, they are commonly organized according to several key criteria, including tracking technique, sensing methodology, and the degree of technological advancement.

Within each of these main classifications, MPPT methods are further subdivided into categories that reflect variations in factors such as the working principle, complexity, implementation, and intended use-case environment. For example, tracking techniques may include perturb and observe (P&O), incremental conductance, and fuzzy logic methods, each offering different levels of accuracy, speed, and computational requirements. Meanwhile, classifications based on sensing can vary between algorithms that rely on voltage, current, or a combination of both for precise tracking of the maximum power point. This layered classification reflects the adaptability of MPPT systems to different photovoltaic (PV) environments, weather conditions, and performance requirements, making it possible for designers to select the most appropriate algorithm based on specific system needs. As a result, MPPT algorithm research continues to expand, incorporating innovative approaches to improve accuracy, response speed, and energy efficiency under diverse operating conditions [22].

With advancements in technology, charge controllers continue to evolve, incorporating advanced control algorithms and additional features to enhance system efficiency and reliability. In [25], the topologies of several popular DC-DC converters used in solar PV systems are described in detail, including the buck, boost, buck-boost, Cuk, Sepic, and flyback converters. Each, along with its mode of operation and the specific advantages and limitations associated with its application in solar PV systems. Furthermore, the paper highlights the key considerations for selecting an appropriate DC-DC converter topology in solar PV applications. Factors such as input voltage range, output voltage requirements, efficiency, cost, and reliability are discussed, providing readers with insights to make informed decisions when choosing a converter topology for a particular solar PV system. The authors also discuss the control techniques employed in DC-DC converters to regulate the output voltage and maximize power extraction from solar PV panels. Control strategies such as (PWM) and (MPPT) are examined, emphasizing their significance in achieving high conversion efficiency and optimal performance.

Charge controllers play a crucial role in regulating and managing the charging and discharging of batteries in photovoltaic (PV) systems, ensuring efficient and safe operation. Charge controllers are essential components in PV systems, providing critical functions such as battery charging regulation, MPPT, battery discharge prevention, load control, system monitoring, data logging, and protection functions to ensure efficient and safe operation of the system [23] Proper selection and sizing of the charge controller are crucial to ensure compatibility with the PV system, battery bank, and load requirements [24]. Table 1 below shows most MPPT techniques used in most industrial and commercial applications [15].

TABLE I. MPPT TECHNIQUES [38]

Technique	***Definition***	***Advantage***	***Disadvantage s***
P&O Perturb & Observe	Utilizing a voltage sensor, comparing output power with the power at the previous perturbing cycle	Simple, low-cost requires minimal hardware, compatible with different types of PV	Low efficiency compared to other MPPT techniques during changing weather conditions, oscillation in output power.
IC Incremental Conductance	Utilizing 2 voltage & Current sensor, compare the instantaneous conductance of the PV solar with its incremental conductance	Rapid and accurate tracking under irradiance and temp changes. Higher efficiency than P&O	More complex hardware Works with limited types of PV solar modules.
Fuzzy Logic	Compares the PV output power with solar Max Power (MPP), then adjust the load resistor to maintain optimal power output	Can handle uncertain data adapt to change caused by weather rapidly	complex hardware compared to P&O and IC

Figure 4 shows the essential structure of a power-split dual transport. In this design, the rotating gear system, along with the engine and generator, work like a variable-ratio drive mechanism. This configuration allows for smooth transitions between power sources. Notably, the energy management approach depends entirely on electrical power to accomplish the move, ensuring efficient energy utilization and optimizing performance. This approach is particularly advantageous in hybrid systems, as it allows for smooth power distribution and enhances the vehicle's ability to handle varying driving conditions while maintaining energy efficiency.

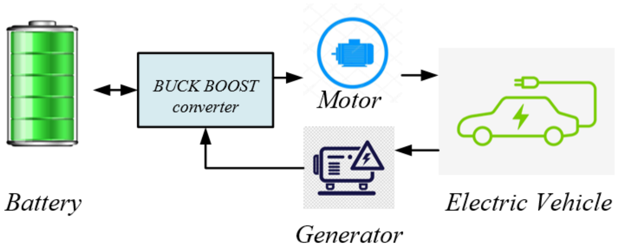

Fig. 4. System Block diagram

III. SIMULATION RESULTS

To validate the findings, a MATLAB/Simulink simulation was performed for a photovoltaic (PV) battery charging and storage system utilizing a bi-directional DC-DC converter. The block diagram depicts the basic construction of a power-split dual motion system, in which the planetary gear, together with the motor and generator, works as a variable ratio gear. In the test scenario, the machine speeds from 10 kilometers per hour to twenty kilometers per hour before slowing back to ten m/s. The power management approach depends exclusively on electricity to achieve this move.

The engine, DC-DC converter, and generator are simulated utilizing blocks of MATLAB/Simulink. These blocks leverage energy-based, system-level equations, enabling efficient simulations while still accounting for conversion losses. This model is highly effective for supporting the design and optimization of the power management strategy, providing valuable insights into the interaction between the electrical components and the power transmission system. This approach ensures an accurate representation of real-world dynamics, making it suitable for designing robust and efficient power management strategies in hybrid transmission systems.

Following acceleration, the generator supplies a consistent flow of power to the DC network, which is powered by the motor. Simultaneously, the motor taps into the battery to supply the necessary power for vehicle acceleration. When decelerating, regenerative braking enables the motor to reverse this process, feeding power back into the battery, thereby enhancing energy efficiency and prolonging battery life as shown figure 5.

Figure 6 presents the voltage and current levels during both the battery's charging and discharging phases, providing a detailed view of the energy exchange process. Figures 7 and 8 offer insights into the current and voltage values of the DC-DC converter and the motor, showcasing the real-time performance of these components. These figures highlight the seamless integration of the motor and converter, ensuring optimal power flow and efficient energy management throughout the operation cycle, thus supporting both dynamic vehicle performance and energy conservation.

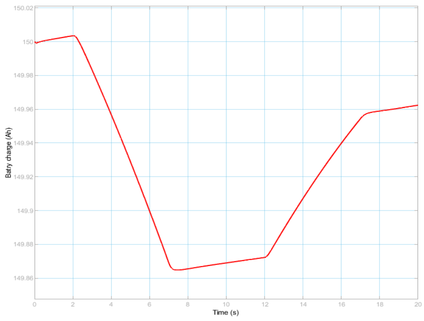

Fig. 5. The charging and discharging operation modes of the battery power PV system

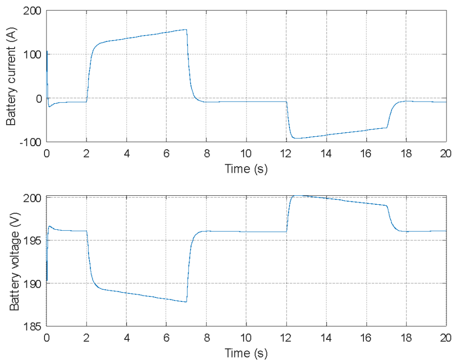

Fig. 6. The Voltage and Current of the battery

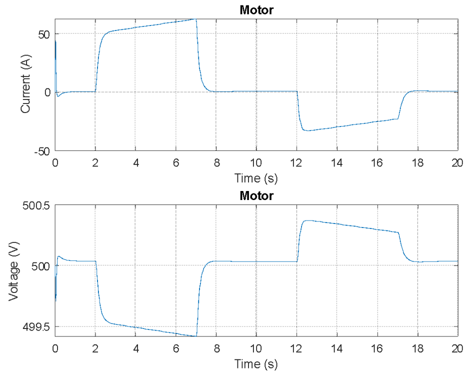

Fig. 7. Voltage, Current, and DC Bus voltage of the battery

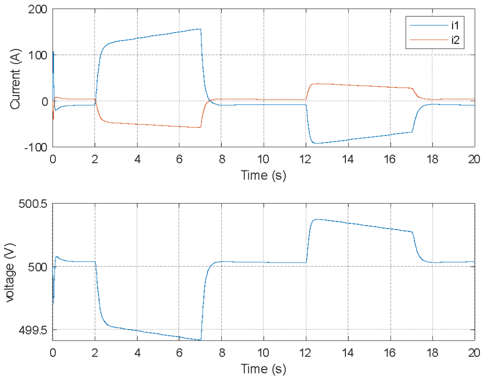

Fig. 8. Voltage, Current of the DC –DC Converter

IV. Conclusion

This investigation emphasizes the efficacy and flexibility of the suggested control techniques for power management in hybrid systems. The system provides smooth and economical operation using a power-split combination transmission with a circular gear, motor, and generator, particularly in scenarios requiring precise power distribution and speed control. The exclusive reliance on electrical power in the maneuver demonstrates the potential for optimizing energy use in modern hybrid applications. Through MATLAB/Simulink simulations and real-world analysis, the bi-directional DC-DC converter demonstrates its effectiveness in controlling energy flow during both acceleration and regenerative braking phases. This study highlights the importance of implementing advanced DC-DC converter topologies and control strategies to improve the performance, efficiency, and safety of hybrid systems. Future work may focus on refining these models for more complex applications, expanding their applicability in electric vehicles and other energy-intensive sectors. The insights gained from this research provide a foundation for further innovations in power management, energy storage, and overall system integration in hybrid and electric technologies.

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