A Reconfigurable Topology for Integration of Removable Batteries in an Electric Powertrain With 400 V and 800 V Compatibility

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***Abstract*—Electric vehicles (EVs) are a sustainable solution for transportation, which on-board batteries play a fundamental role. To enhance the flexibility of EV energy management and contribute to overall performance improvements in the electric powertrain, the integration of a removable battery emerges as an alternative approach. This solution is suitable for both the widely adopted 400 V bus standard and the emerging 800 V standard, which is gaining acceptance in the commercial vehicle market due to its promising features. This paper presents a reconfigurable topology with the ability to connect a removable battery to both the 400 V and 800 V buses. An externally charged removable battery offers an additional level of flexibility, allowing for external charging and the option to adjust the EV capacity based on the chosen route. The proposed reconfigurable topology can operate at both the 400 V and 800 V standards without any external switch to adapt to each voltage level. Thanks to the modularity of the proposed technology, voltage and current maximum ratings of the semiconductors are not increased due to the use of the 800 V standard. The topology is based on the Dual Active Bridge (DAB) converter utilizing the Input Parallel Output Parallel (IPOP) and the Input Parallel Output Series (IPOS) configurations. Experimental results on a downscaled prototype demonstrate the performance and feasibility of the reconfigurable topology.**

***Index Terms*—DC-DC converter, dual active bridge, electrical vehicles, reconfigurable topology, removable battery, 800 V standard.**

I. Introduction

Electric vehicle (EV) has been a major focus of interest in recent years, due to the widespread effort to develop transportation methods with a reduced environmental footprint [1], [2]. An essential component of an EV is the on-board battery, Which is in charge of storing and supplying the energy not only for the powertrain system but also for the auxiliary systems for the whole vehicle. The most common power architecture for EVs is shown in Fig. 1. A power management system is responsible for charging and discharging the battery according to the driving conditions and overall requested power. Along with the Battery Management System (BMS), this also determines the optimal operating point. Capacity and technology of the battery are crucial for overall performance [3]. This performance can be enhanced and made more flexible by incorporating additional batteries connected to the DC bus, capable of operating collectively or independently [4]. One proposal in power architecture of an EV with multiple batteries is shown in Figure 2. Each battery is equipped with its own BMS, complemented by a central controller known as the Battery Unit Management System (BUMS).

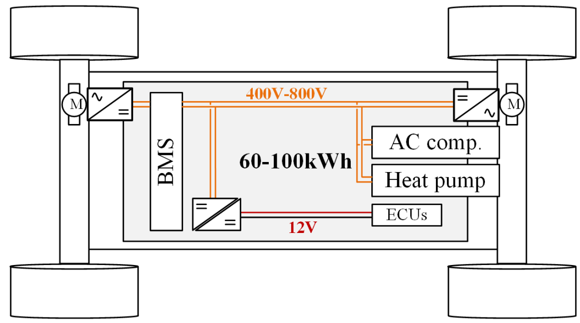


Fig. 1. EV Power architecture.

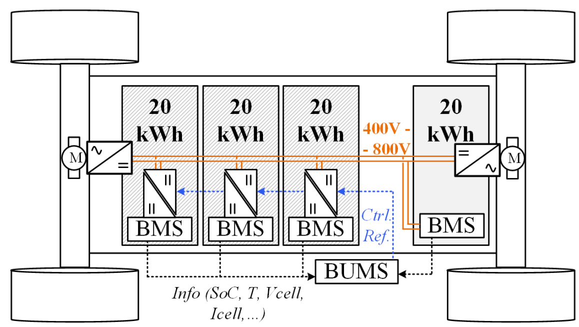


Fig. 2. EV Power system with multiple batteries.

The on-board battery (main battery) primarily supplies higher power and operates for the majority of the time. In specific scenarios, additional batteries come into play delivering lower power. They are activated, for instance, during startup or when high current peaks occur [5]. In addition, they can store energy harvested from the EV, such as during regenerative braking, and subsequently feed it back into the DC bus to supply the powertrain system. The potential to integrate multiple batteries for EV operation enables a reduction in the capacity of the on-board battery, i.e. from 60 kWh or 80 kWh to 20 kWh, and some external removable and swappable batteries, each with a capacity of 20 kWh, to obtain the same capacity. Furthermore, this approach to battery integration facilitates the utilization of batteries with diverse technologies, leveraging their respective strengths and advantages [6]. However, despite the benefits of connecting extra batteries, there is an immediate trade-off of an increased component count, resulting in higher vehicle weight, and added complexity to the energy management system.

A removable battery is a particular case of additional batteries. An externally charged removable battery offers an additional level of flexibility, allowing for external charging and the option to adjust the EV capacity based on the chosen route [7]. Energy stored can also be useful in external applications of an EV, such as residential use or as a power source for another EV. The removable battery may be a second-life battery and could potentially employ a different technology from the on-board battery. In this scenario, an existing battery is utilized to complement and optimize the operation of the on-board battery [8].

The connection of the removable battery to the DC bus is established through a DC-DC energy conversion topology. According to the current standard in lower power levels in passenger EVs (vehicles Class One in U.S. standard, or N1 in E.U. standard), the DC bus nominal voltage is 400 V. However, certain publications suggest the potential utilization of buses operating at 800 V [9]. Increasing the DC bus voltage offers notable advantages, including higher power and reduced current. Furthermore, this results in a shorter charging time [10]. Presently, Class 1 EVs equipped with an 800 V DC bus constitute 17 % of the total, a percentage that will increase in the coming years [11]. When both EVs equipped with a 400 V DC bus and those adhering to an 800 V standard coexist, it is advisable to employ reconfigurable energy conversion topologies capable of adapting the voltage requirements of the systems 400 V and 800 V. Several publications discuss reconfigurable topologies capable of operating at two different voltages (one being twice the other). A reconfigurable topology based on a Dual Active Bridge (DAB) employs series and parallel switches to adapt to each voltage bus is presented in [12]. Other works specifically focused on battery chargers capable of operating over a wide range of voltages, compatible with the standard 400 V and 800 V buses [13], [14]. These topologies are based on a phase-shifted full bridge with a capacitor branch and a switch at the input port [13], and on an LLC resonant converter with dual secondary sides and three external switches [14]. One drawback of these reconfigurable topologies lies in the need for switches to change between voltage levels, leading to an increased component count and a reduction in conversion efficiency.

This paper introduces a reconfigurable topology capable of connecting a removable battery to both 400 V and 800 V buses. The proposed topology relies on the DAB converter and does not use external switches. This reconfigurable topology enables straightforward adaptation to the DC bus standard without subjecting the semiconductor operation over the current and voltage maximum ratings. The structure of this paper is as follows. Section II introduces the reconfigurable topology for linking the removable battery to either the 400 V or 800 V DC bus. The control scheme is included in Section III. A downscaled experimental prototype is built and validation tests are conducted in Section IV. Finally, the conclusions are presented in Section V.

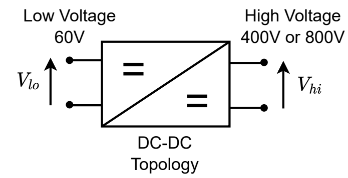


Fig. 3. Nominal voltage specifications of the modular topology.

II. Modular Topology for HV-DC bus

A. Modularity and Reconfiguration

There are two primary challenges in broadly defining the reconfigurable topology: first, establishing its structure, and second, determining the reconfiguration method. The initial task is to delineate the structure of the reconfigurable topology. A modular approach is applied in this study. This approach poses the interconnection of fundamental units (modules) enabling adaptation to varying voltage and current levels. The modular approach is a trend to scale towards higher powers as seen in multilevel converters, without increasing the voltage or current stresses on the semiconductor devices within each fundamental unit of the power converter [15]. Implementing a modular approach brings additional advantages. First, it simplifies maintenance and repair procedures, allowing for the replacement of individual modules without disrupting the entire system functionality. In addition, modular design contributes significantly to cost effectiveness in manufacturing. By simplifying the production process and leading to a reduction in manufacturing expenses [16].

In the modular approach, there are two primary trends based on the processed power level: i) partial power processing, and ii) full power processing. In the case of shared power, it is possible for some modules to process fixed power, while the remaining modules provide variable power, or all modules can process variable power. In the case of full power processing, the modules are in cascade connection, and all process the entire power load. The only variables that change in each conversion stage are voltage and current. In the context of EVs, particularly in the connection of a removable battery to the DC bus, partial power processing is recommended. This choice allows for greater flexibility in the joint operation of the on-board battery and the removable battery. The common approach to achieve partial power processing is based on serial or parallel connections between modules. Possible configurations include Input Parallel Output Parallel (IPOP), Input Parallel Output Series (IPOS), Input Series Output Parallel (ISOP), and Input Series Output Series (ISOS) [17]–[20].

The proposed reconfigurable topology should facilitate connection to standard 400 V and 800 V DC buses. The nominal voltages are illustrated in Fig. 3. The removable battery is connected to the low-voltage side, while the high-voltage side corresponds to the high-voltage DC bus within the EV

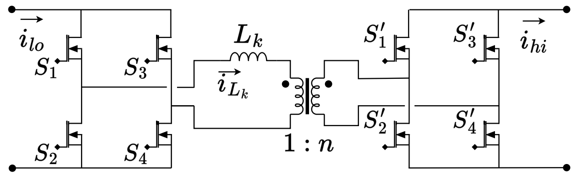


Fig. 4. Structure of the DAB converter.

architecture. For outputs reconfigurable to both 400 V and 800 V buses, with a constant input much lower than the output voltage, it is advantageous to connect in parallel at the input, and either in series or in parallel at the output, depending on the DC bus standard. Specifically, IPOP is suitable for the 400 V standard, while IPOS is recommended for the 800 V standard. For instance, in the case of only two modular converters, their inputs are always connected in parallel, and the outputs of both modules are connected in parallel for the 400 V standard. Conversely, the outputs are connected in series for the 800 V bus.

The next challenge, following the establishment of the modular topology, involves reconfiguring it to align with the voltage level of the DC bus. To adapt to two significantly different voltage levels can be accomplished through external switches [12]–[14]. However, this approach not only increases the component count but also decreases the energy conversion efficiency. Consequently, it is advisable to avoid using external elements whenever possible. In the proposed reconfigurable topology, this challenge is tackled by selectively activating or deactivating the semiconductors within one of the modules (modular converters).

B. Modular converter and Topology

The DAB converter is chosen as the simplest module in the proposed reconfigurable topology. DAB is recognized for its excellent control and efficiency characteristics [21]. This converter presents special interest in the field of EVs due to its key features such as galvanic isolation and bidirectional operation [22]. The structure of the DAB converter is depicted in Fig. 4. The DAB can process power to voltage levels of both 400 V and 800 V. However, it does not perform optimally in both cases (i.e. with a wide voltage range). The challenges related to achieving optimal performance and compatibility with both 400 V and 800 V standards are met through the implementation of a modular approach. As it mentioned before, DABs are connected in IPOP for 400 V and IPOS for 800 V. In both scenarios, each DAB operates under similar design conditions (voltage conversion from 60 V to 400 V), ensuring high conversion efficiency and employing 600 V/650 V breakdown voltage power transistor in the high-voltage side.

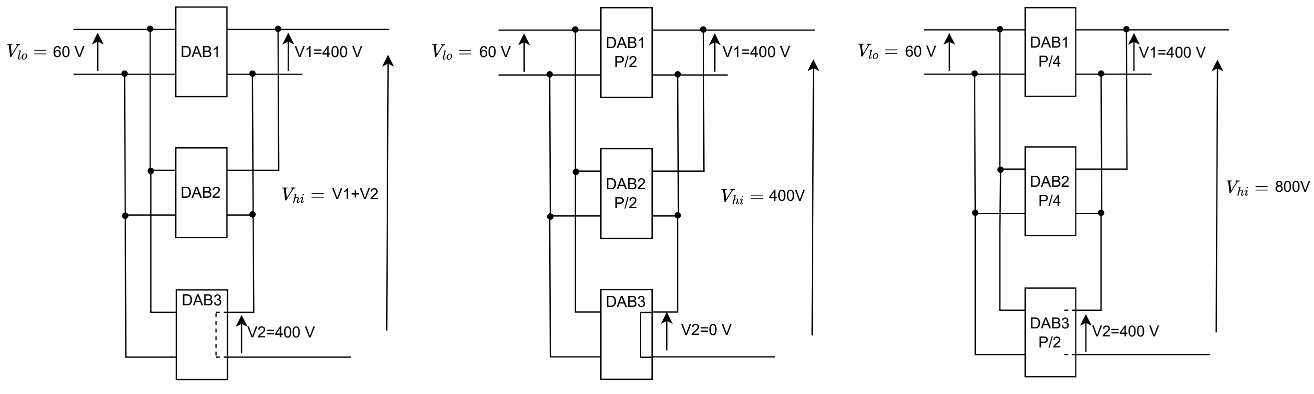
To ensure both the reconfigurability of the topology and that each module processes a maximum a part of the total power, an additional module is required, resulting in a total of three modules. The proposed topology is depicted in Fig. 5(a). Two modules (DAB1 and DAB2) always operate in IPOP configuration and process a portion of the total power (P). The additional DAB (DAB3) allows current to pass through without power processing in the 400 V scenario. In order to achieve this, the MOSFETs of the high-side bridge are continuously turned on, while the low-side MOSFETs are turned off (open-circuit). In the 800 V standard, DAB3 is connected in series with the parallel connection of DAB1 and DAB2. In each scenario, the DAB module is designed to supply a maximum power of $P/2$, making $P/2$ a crucial design criterion for constructing each DAB. The configuration for the 400 V standard is depicted in Fig. 5(b). It is evident that only DAB1 and DAB2 are in operation, with each delivering half of the power ($P/2$). Meanwhile, the configuration for the 800 V standard is illustrated in Fig. 5(c). In this setup, all three modules are involved in power transformation: DAB1 and DAB2 each contribute $P/4$, while DAB3 supplies the remaining power ($P/2$).

III. Control Schemes

The reconfigurable topology manages the charging and discharging operations of the removable battery. When the battery has enough charge, the topology transforms the power required by the DC bus, leading to operation in current mode. Conversely, when the state of charge of the battery is low, the topology operates in voltage mode to regulate the battery charging process. This global control action of the reconfigurable topology implies regulating each modular converter in current or voltage mode based on the DC bus level.

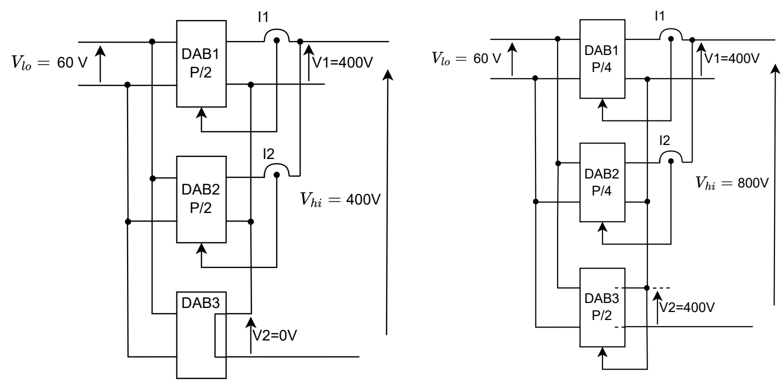
Before addressing the control of the reconfigurable topology, it is crucial to determine the required number and type of sensors for measurements, whether for current or voltage. Modularity seen from the manufacturing process itself implies the manufacture of equivalent modules, and therefore it is sensible to consider one current sensor and one voltage sensor per module. This approach allows each module to independently regulate either current or voltage, and consequently, manage power effectively. In practice, the feasibility of current or voltage control options primarily determined by the specific characteristics of the modular converter. But The DAB demonstrates notable control flexibility as one of its key characteristics [23].

In a modular topology, redundant measurements may arise, and there is potential for certain sensors to be omitted. On one hand, in the IPOP connection flexibility is maximized with the requirement of only one current sensor per DAB. On the other hand, the IPOS connection imposes both voltage balancing and current regulation [24]. In an IPOS connection with n DABs, one current sensor and $n-1$ voltage sensors are required. This configuration implies that one DAB regulates the current passing through the series connection, while the remaining DABs adjust their voltage to align with the reference level. For instance, in a basic scenario involving two modular converters, DAB1 takes charge of current control, while DAB2 focuses on voltage regulation. The voltage reference for DAB2 is set at half of the bus voltage, ensuring that DAB1 being



(a) (b) (c)

Fig. 5. Modular topology and configurations for standard bus DC voltages: a) overall scheme, b) 400 V standard, c) 800 V standard.



(a) (b)

Fig. 6. Modular topologies control schemes: a) 400 V standard, b) 800 V standard.

current-controlled, naturally maintains a voltage regulation in difference between the DC bus and the DAB2 voltage. This scenario applies whenever the control technique relies solely on feedback from the variable that needs to be regulated.

The suggested reconfigurable topology consists of three identical DABs, each designed to operate within a voltage range of 60 V to 400 V, with a maximum power output of 500 W. Specifically, DAB1 and DAB2 function in parallel, while DAB3 is connected in series (Fig. 5). In the 400 V scenario, the power-processing converters DAB1 and DAB2 are controlled in current mode as shown in Fig. 6(a), making it possible for each one to operate with a different reference. In the 800 V scenario depicted in Fig. 6(b), DAB1 and DAB2 are assigned the task of regulating the current, while the DAB3 focuses on maintaining the voltage balance in the series connection.

IV. Experimental Results

A downscaled prototype has been built to experimentally validate the 400 V and 800 V connections at the output port. The reconfigurable topology prototype is based on 2 DAB units (DAB1 and DAB2), each one of 500 W (see Fig. 7). Table I displays the key characteristics of each DAB. The primary distinction between both converters lies in the configuration of the leakage inductance (L_k). In DAB1, L_k is an external component connected in series with the isolation transformer (Fig. 7(b)). Conversely, in DAB2, L_k is integrated within the transformer itself (Fig. 7(b)). Secondly, intentionally distinct leakage inductances have been chosen to assess the feasibility of the proposed reconfigurable topology for non-identical modular converters.

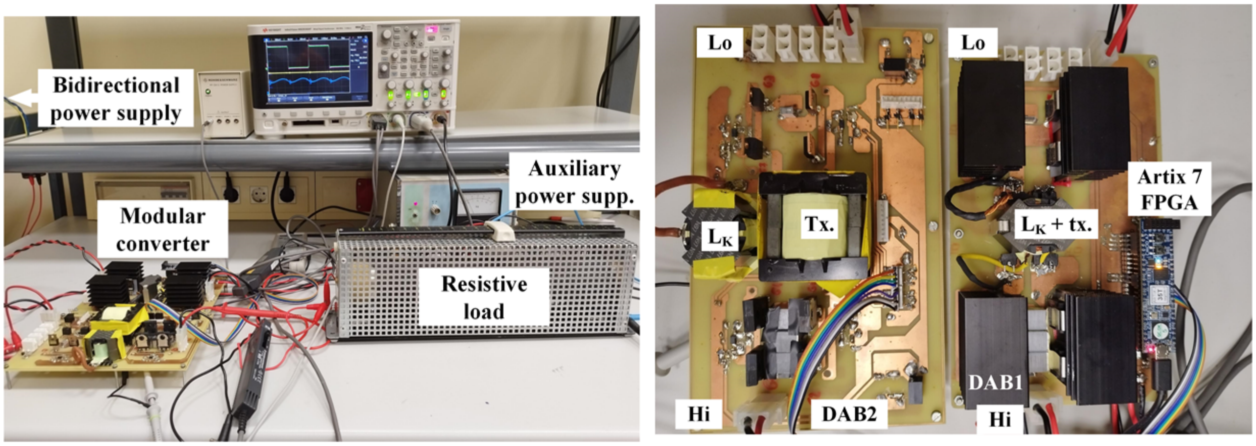
TABLE I
MAIN PARAMETERS OF THE DABS IN THE RECONFIGURABLE TOPOLOGY

Parameter	DAB1	DAB2
L_k [μH]	6.2	3.3
n	8	8.4

The DAB converters are controlled by the Artix 7 FPGA (refer to Fig. 7), operating to fixed switching frequency of 100 kHz. Some tests were performed on both IPOP and IPOS connections with a resistive load, in accordance with the configurations depicted in Fig. 8.

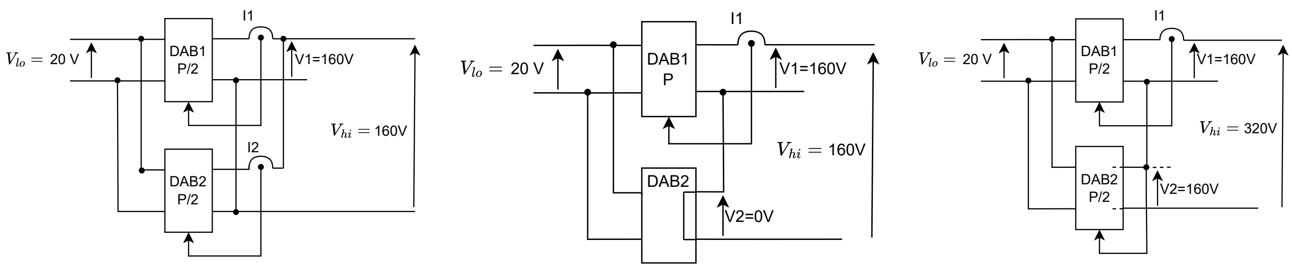
A. IPOP Test

While the IPOP connection is a well-documented and established configuration, two experiments were conducted to verify the topology performance (see configuration in Fig. 8(a)). These experiments include both equal and varying current



(a) (b)

Fig. 7. a) Experimental setup for testing, b) DAB description (DAB1: DAB with non-integrated leakage inductance; DAB2: DAB with integrated leakage inductance).



(a) (b) (c)

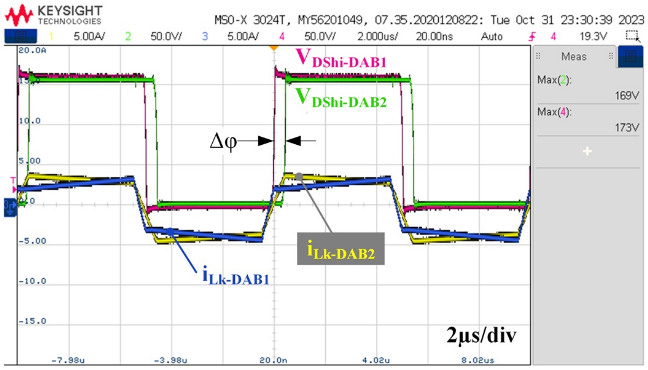
Fig. 8. Experimental validation setups for the reconfigurable topology: a) IPOP b) IPOS 160 V, c) IPOS 320 V.

references, while maintaining a constant power consumption by the resistive load. Test conducted involved input and output voltage configurations of 20 V - 160 V. The experimental waveforms are shown in Fig. 9 and Fig. 10. Fig. 9 shows the experimental results of the modular converters supplying equal power to the load (equal current references). Each subfigure displays the voltage waveform between the drain and the source in one of the high-voltage side MOSFETs of the respective DAB (CH 2 ($V_{DShi-DAB1}$), CH 4 ($V_{DShi-DAB2}$)). It can be noticed that a phase-shift exists between these voltages ($\Delta\varphi$), corresponding to the difference between the phase shift of both modular converters operation. Additionally, Fig. 9(a) showcases comparable behaviors in the current waveforms of the inductors L_k ($i_{Lk-DAB1}$, $i_{Lk-DAB2}$), while Fig. 9(b) shows the output currents of each DAB (CH 1 ($i_{hi-DAB1}$) and CH 3 ($i_{hi-DAB2}$)). This opposing pattern in the current ripples yields a total output current approximately constant, as evident in Fig. 9(c) (see CH 1). It is important to note that the present balance condition arises from the distinct operating points set for each DAB, influenced by varying L_k values. On the other hand, results in Fig. 10 show both DABs operating under unbalanced power condition (different current references). It is worth highlighting that the output voltages in CH 2 and CH 4 remain consistent and identical to those observed in the previous experiment (refer to Fig. 9). Notably, the average output current of each DAB differs (see signals in CH 1 and CH 3 in Fig. 9(a)), yet the total current remains nearly constant and without ripple (CH 1 in Fig. 9(b)). An interesting conclusion from these initial tests is that designing diverse modules and implementing distinct operational strategies can lead to enhanced overall performance.

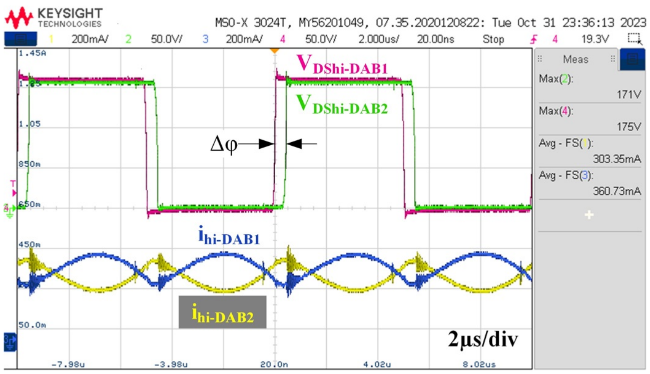
B. IPOS Test

This study emphasizes the IPOS connection where the true research contribution lies. It is meaningful to verify the operation at 400 V by short-circuiting the high-voltage bridge MOSFETs of one DAB, as well as examining the 800 V connection where both DABs are operating. The tests involved input and output voltage configurations of 20 V - 160 V (see configuration in Fig. 8(b)) and 20 V - 320 V (see Fig. 8(c)). The experimental results for both scenarios are respectively presented in Fig. 11 and Fig. 12. In each figure, the current i_{Lk} and the voltage (V_{DShi}) for each DAB are shown. In the low-voltage scenario (refer to Fig. 11), only DAB2 is operating, hence the waveforms for DAB2 are null (signals CH 1, CH 2). CH 3 displays the voltage waveform $V_{DShi-DAB1}$, measuring approximately 160 V peak value, while CH 4 depicts the current waveform $i_{hi-DAB1}$.

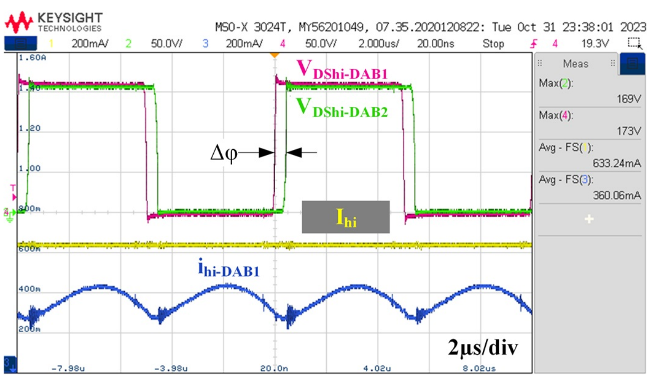
Conversely, in the high-voltage scenario, both DABs are switching (see Fig. 12). One of them is responsible for voltage regulation and the other one regulates the current supplied to



(a)



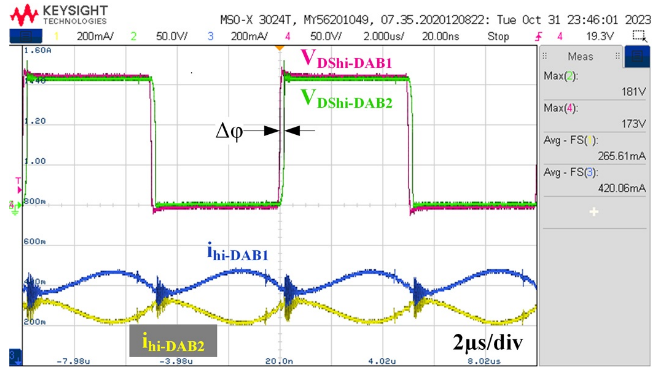
(b)



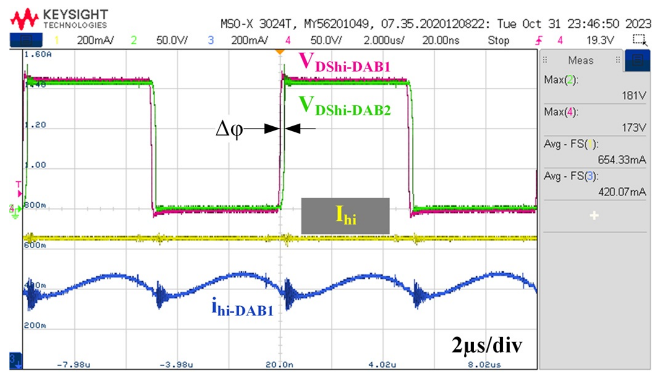
(c)

Fig. 9. Experimental waveforms of the reconfigurable topology in IPOP connection with modular converters supplying the same power.

the load. Tests were conducted using various voltage references, while keeping the current constant. Results for DAB1 are presented in CH 1 ($i_{Lk-DAB1}$) and CH 2 ($V_{DShi-DAB1}$), while corresponding results for DAB2 can be found in CH 3 ($i_{Lk-DAB2}$) and CH 4 ($V_{DShi-DAB2}$). In Fig. 12(a), the waveforms show approximately equal voltages of 160 V peak value (voltage balance). However a notable disparity is observed in the current waveforms because of the variations in the leakage inductances of the DABs. Additionally, it can be noted that each converter operates with distinct phase shift due to the differing values of L_k, however voltage balance is obtained. In Fig. 12(b,c,d) each converter operates with different voltages. In the results shown in Fig. 12(b), DAB1



(a)



(b)

Fig. 10. Experimental waveforms of the reconfigurable topology in IPOP connection with modular converters supplying different powers.

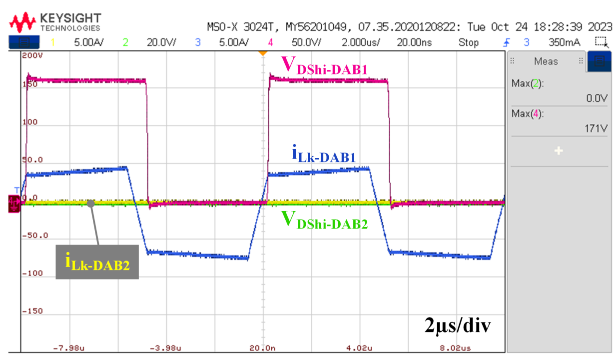
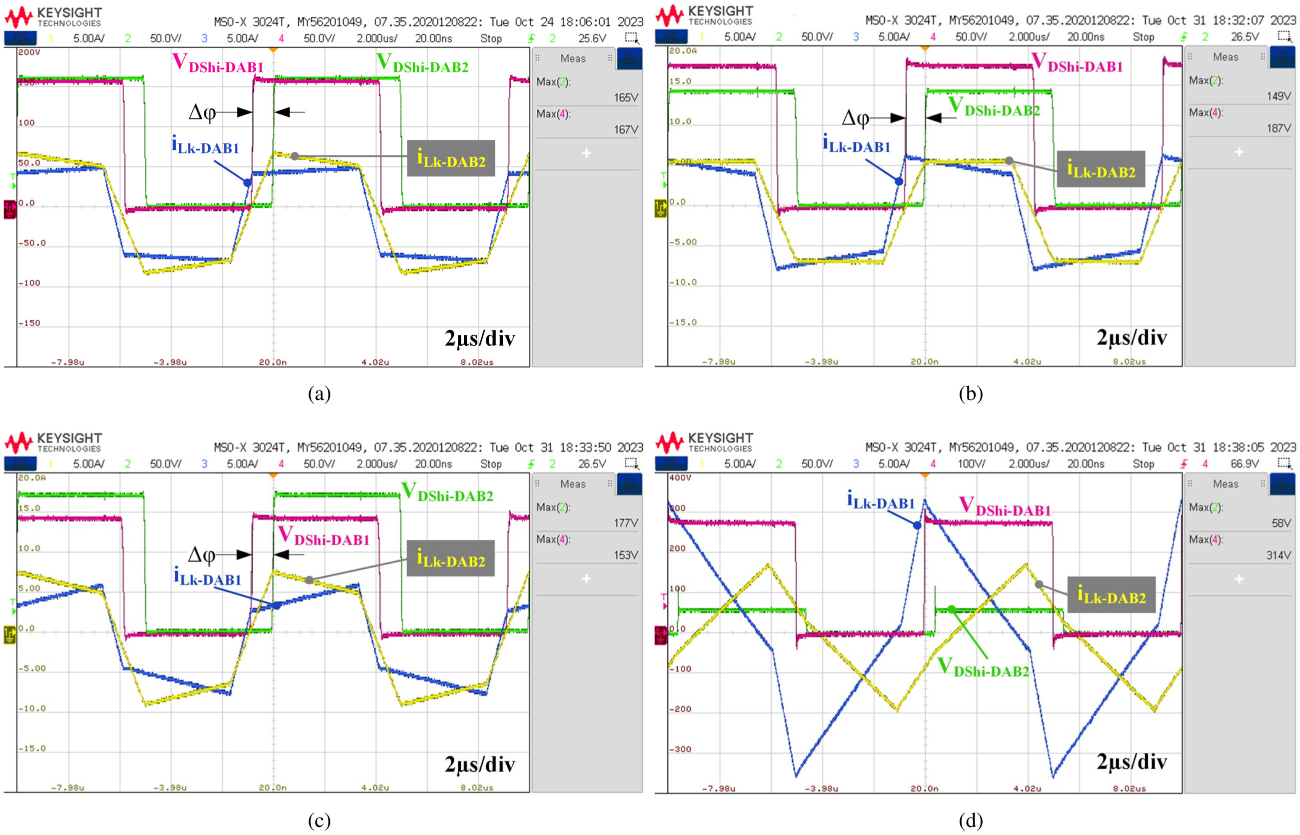


Fig. 11. Experimental waveforms of the reconfigurable topology with low-voltage at the output port.

supports a higher voltage level compared to DAB2 (noted by the higher waveform amplitude in CH4 compared to CH2). Fig. 12(c) shows that DAB2 supports greater voltage. The case study depicted in Fig. 12(d) showcases a notable unbalanced voltage, which is also reflected in significant disparities in the i_{Lk} current waveforms.

While voltage balance is the inherent control preference in the IPOS configuration, the findings demonstrate that it is feasible to operate the modular topology with distinct output voltages for individual modular converters according to the specific application. Furthermore, it is reasonably to



(a) (b) (c) (d)

Fig. 12. Experimental waveforms of the reconfigurable topology in IPOS connection with modular converters operating with the same voltage (a), and with diferent voltage at their output ports (b,c,d).

utilize non-identical modular converters in scenarios involving voltage unbalance.

V. Conclusions and Future Work

This paper introduces a reconfigurable modular power topology that enables the integration of removable batteries into the electric powertrain system, providing greater flexibility in energy management. The topology is designed to operate seamlessly with both 400 V and 800 V standards, facilitating efficient interfacing with on-board removable batteries. Preliminary results demonstrate the successful validation of the reconfigurable topology without the need for external switches in both low- and high-voltage testing. Additionally, the intentional selection of distinct leakage inductances showcases the system ability to accommodate non-identical modular converters, underlining its flexibility and potential for practical applications. By employing a modular approach, each converter can be individually configured with both a current sensor and a voltage sensor. The precise number of sensors required for each application is determined by considering the interconnection and total quantity of connected modules. Future research efforts will focus on refining control loops and advancing the development of a higher-power prototype.

Acknowledgment

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