

# A Modular Interleaved-Based DC-DC Converter Topology for EV Fast Chargers

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**Abstract**—The diffusion of electric mobility continues to grow, which requires that systems associated with electric vehicle (EV) charging keep up with this growth. Furthermore, it is important to continue the technological development of such systems to respond to faster and more efficient charging, to enrich the user experience. Aligned with such perspective, this paper proposes a modular interleaved-based DC-DC converter topology for electric vehicles fast chargers. The proposed DC-DC converter topology is based on a set of configurable DC-DC power modules with independent power inputs and single parallel power output. It is proposed to be used in high-charging power stations, with internal configuration based on multiple isolated DC-DC power conversion stages, where the proposed modular DC-DC converter topology is connected to perform the DC interface directly with the EV battery. With the proper control, the proposed modular DC-DC topology operates in interleaved-based strategy, ensuring a split current among the DC-DC modules, and a reduced ripple in the output current, despite not being a native interleaved topology. The output ripple current of each DC-DC module presents a frequency that matches twice the switching frequency. The results presented in this paper validate the proposed modular DC-DC topology, as well as the proposed control for steady- and transient-state.

**Keywords**—*electric vehicle, fast chargers, modular DC-DC converter topology, DC-DC module, interleaved-based control.*

## I. INTRODUCTION

Mainly due to the technological developments in the last two decades, the transition from conventional vehicles to electric vehicles (EV) is ongoing, forcing the necessity of continuous developments and research, both from the perspective of commercial companies and academia [1][2]. In this transition, an important topic that still requires the most attention is the energy storage system, typically using batteries [3]. However, as alternative, supercapacitors are also gaining preponderance as an option [4]. The emergence of new battery technologies and associated systems is a huge challenge for the continued development and investment in EV [5]. However, the development of new solutions that reduce charging times, i.e., faster charging rates, which involves transferring a lot of power in a short time, is no less important to achieve a quick and effective transition to EV [6][7]. To meet this challenge, more than the improvement in terms of control algorithms, are the new approaches needed in terms of component use, as well as new power electronics converter topologies.

Currently, there are two main possibilities for charging EV batteries, using an on-board or an off-board charger. In addition, other possibility is gaining more preponderance, which is the wireless charging technology, where part of the charging system is off-board and the other is on-board [8][9]. In addition of the distinction about on-board and off-board chargers, other difference relies on the charging rates, since they can be classified in different levels and modes [10]. Generically, charging rates varies from few kW at domestic situations to hundreds of kW in specific public charging facilities [11]. Globally, as occurs in any electronic-based technology, also for EV chargers the trend is to substantially increase the power rating, while decrease volume, weight, and cost. Nevertheless, to ensure the previously mentioned growing, numerous challenges must be overcome with diverse levels of priority. Concerning EV chargers, it is imperative a mass adoption of domestic and public chargers (e.g., also targeting EV chargers in parking garages). For public chargers, EV fast chargers with high power levels are fundamental for ensuring low charging periods and consequently to mitigate effects of the called “range anxiety” [12].

In the context of EV fast chargers, the power electronics architecture is outside the EV (i.e., off-board charging), permitting more flexibility in terms of weight and size optimization. EV fast chargers are based on two main interfaces, namely an AC three-phase active front-end interface with the power grid and a DC back-end interface directly connected the EV battery [13]. For ensuring high power levels, then it is necessary increase the power of the EV charger, consequently, the challenge relies on the topology, both for the AC-DC and for the DC-DC. Numerous topologies can be embraced for the AC-DC, containing passive and active converters (as well as multilevel or interleaved options) with different operating possibilities [14][15]. In such case, it is priority ensuring balanced and sinusoidal currents, with controlled active and reactive power. For the DC-DC, also numerous topologies can be embraced, where a key different relies on the isolation or not [16][17]. Moreover, with the prospect of guaranteeing adjustable power levels, modular structures are also possible for EV fast chargers, suggesting a set of supplementary advantages for EV fast chargers [18][19][20], allowing a significant power increasing (including adaptable voltage and current levels), and avoiding the limitations of traditional interleaved-based solutions.

In this context, a modular interleaved-based DC-DC converter topology for EV fast chargers is proposed in this paper. It can be identified several key features, which are listed as: (i) configurable to an undefined number of individual DC-DC power modules, each one with independent power inputs (e.g., from dual active bridge converters) and combined between them to form a single power output; (ii) the number of DC-DC modules can be adjusted according to the requirements of the high-charging power stations, and each one can be individual controlled in terms of operating power (e.g., can be useful in a case of malfunctioning or overheating of an individual DC-DC module); (iii) internally, each individual DC-DC module is capable of operating in interleaved-based control, offering an individual output current with reduced ripple, whose frequency matches the double of the modulation frequency; (iv) in addition of the previous point, the different DC-DC modules are controlled between them in interleaved-based control (i.e., in addition of the internal control) making possible to obtain a combined output current, whose ripple presents a frequency that is the quadruple of the number of individual DC-DC modules (e.g., for 2 modules with individual modulation frequency of 20 kHz, the output current has a ripple with a frequency of 80 kHz); (v) the output of the proposed DC-DC topology (i.e., the parallel output association of the individual DC-DC modules) makes a direct interface with the EV battery, permitting a voltage or current control; (vi) module-shedding can enable high-frequency operations throughout the whole power range by dynamically enabling only the strictly necessary amount of modules at any given power level.

After highlighting the main features of the proposed modular interleaved-based DC-DC topology for EV fast chargers, the topology is presented and detailed described in section II, while the proposed control and modulation for each individual DC-DC module, as well as for a combination of several DC-DC modules, is described in section III. The key results are presented in section IV to confirm the viability of the proposed modular interleaved-based DC-DC topology, and the conclusion are given in section V.

## II. MODULAR INTERLEAVED-BASED DC-DC TOPOLOGY FOR EV FAST CHARGERS

The introductory context of the proposed modular interleaved-based DC-DC topology for EV fast chargers is illustrated in Fig. 1. Generically, the presented EV fast charger is based on: (i) a power stage of an AC three-phase three-wire interface with the power grid; (ii) a power stage isolated in high-frequency (e.g., based on a three-level dual active bridge with a split-capacitor); (iii) and a power stage of an DC-DC interface with the EV battery, allowing a voltage or a current control. In this figure is emphasized the modular DC-DC, performing the interface between the output of the isolation power stage and the EV battery, which has a parallel combination in the output. For increasing the number of DC-DC modules, then it is necessary to increase the number of outputs in the isolation power stage (e.g., which can be accomplished by multiple windings in the high-frequency transformer or by combing more stages with high-frequency transformers).

More specifically, the architecture of the proposed modular interleaved-based DC-DC topology for EV fast chargers is presented in Fig. 2. Each DC-DC module is composed by two full-controlled semiconductors (IGBTs or MOSFETs), by two passive semiconductors (diodes), and by two power inductors.

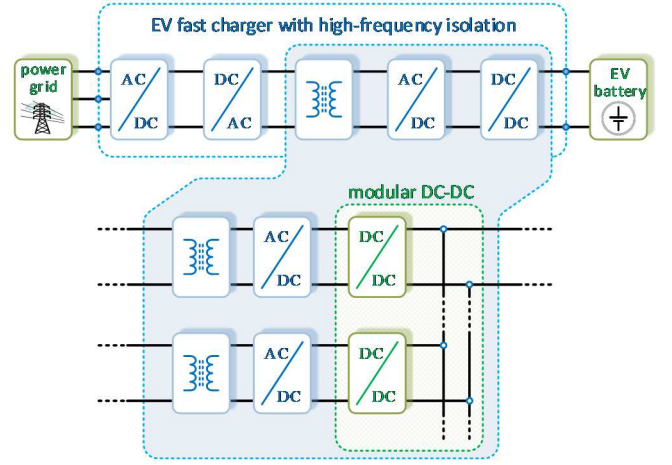


Fig. 1. Context of an EV fast charger with high-frequency isolation where the proposed modular interleaved-based DC-DC converter topology can be introduced.

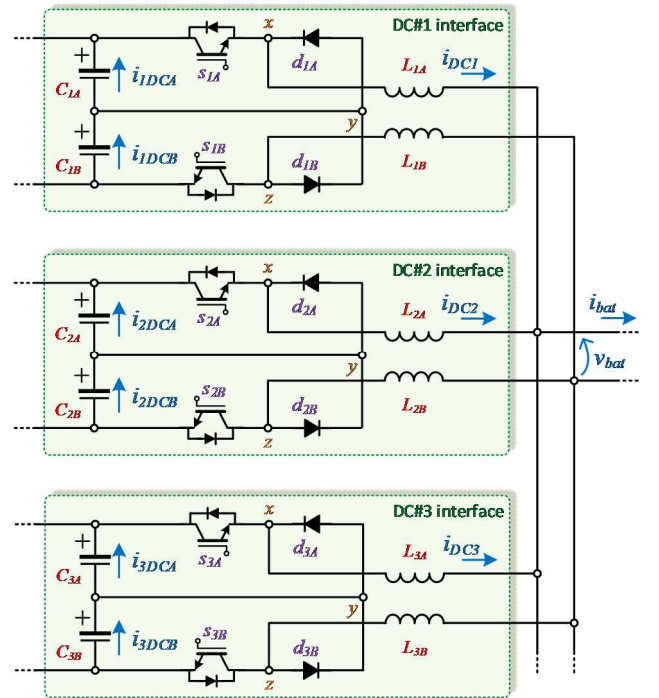


Fig. 2. Proposed modular interleaved-based DC-DC converter topology for EV fast chargers.

An important feature of the proposal relies in the fact that a single current sensor is enough for controlling the output current. As can be verified in Fig. 2, it is a modular structure, allowing several DC inputs and a single DC output, linked in parallel for ensuring a high current charging. As presented in the figure, the topology operates in unidirectional mode, but if bidirectional operation is demanded, in order to allow both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operation modes, the diodes can be replaced by controlled power devices, thus permitting bidirectional operation to the proposed topology. Obviously, in such circumstances, it is necessary to change the control algorithm. One of the main advantages of the proposed modular interleaved-based DC-DC topology is not only in the output parallel association, but in the proposed modulation, which must be adjusted in function of the number of considered DC-DC modules, as exhaustive elucidated in section III. The current in each DC-DC module is individually controlled, which is relevant for ensuring other degrees of freedom in terms of power control.

### III. CONTROL AND MODULATION OF THE MODULAR DC-DC TOPOLOGY

Analyzing Fig. 2, it is evident that the output current ( $i_{bat}$ ) is the sum of the individual controlled current in each DC-DC module (i.e.,  $i_{DC1}, \dots, i_{DCn}$ ). Internally, both IGBTs are always controlled, but presenting a phase-phase of  $180^\circ$  between them. With such strategy, thus, it is possible to achieve a current in each DC-DC module with a ripple frequency ( $f_{\Delta iL}$ ) twice of the individual frequency of the PWM in each IGBT ( $f_{sw}$ ):

$$f_{\Delta iL} = 2f_{sw} . \quad (1)$$

This is achieved by considering two independent carriers, but both with the same amplitude and frequency, but lagged  $180$  degrees: the modulator must be the same for both cases since is controlled a single output variable (in this case the current). If adding more DC-DC modules, two situations can arise in terms of output current: (i) the control of each DC-DC module is totally independent and the resultant output current (i.e., the sum of currents from  $n$  DC-DC modules) will present a current with a ripple, whose frequency is the same as the current in each DC-DC module; (ii) the control of each DC-DC module is strategic combined (i.e., requiring a synchronized control algorithm between DC-DC modules) and the resultant output current will present a current with a ripple, whose frequency is drastically reduced. The relation between the frequency of the ripple in the output current ( $i_{bat}$ ), the number of DC-DC modules ( $n$ ), and the switching frequency of any IGBT (but assuming the same value for all IGBTs) is given by:

$$f_{\Delta iL} = n 2f_{sw} , \quad (2)$$

thus, e.g., for  $f_{sw} = 20$  kHz and  $n = 3$ , the resultant ripple will present a frequency of  $120$  kHz; this is an important feature of the proposed modular interleaved-based DC-DC topology for EV fast chargers. In this case of adding more DC-DC modules, obviously, the complexity of the control increases (the communication between DSP is indispensable, but it is out of the scope of this paper). Obviously, the number of carriers is proportional to the number of IGBTs, and all carriers presents the same amplitude and frequency, but in addition of the phase-shift ( $180^\circ$ ) between IGBTs of the same DC-DC module, a phase-shift between DC-DC modules must be introduced ( $\phi_{IGBTnA}$ ), which is given by:

$$\phi_{IGBTnA} = \frac{360^\circ}{2n} . \quad (3)$$

This phase-shift must be implemented between the top IGBTs of each DC-DC module (IGBTs  $s_{nA}$ ), therefore, for the bottom IGBTs ( $s_{nB}$ ), the implemented phase-shift ( $\phi_{IGBTnB}$ ) is given by:

$$\phi_{IGBTnB} = \frac{360^\circ}{2n} + 180^\circ . \quad (4)$$

Based on this PWM strategy it is possible to achieve an output current ( $i_{bat}$ ) with a very low-ripple and high-frequency, which is favorable for EV fast chargers. In addition of the PWM strategy, obviously, a current control is also necessary. For that, different possibilities can be adopted, including classical PI or predictive based on continuous control set. For the purpose of validation in the context of this paper, the individual current in each DC-DC module ( $i_{DC\#}$ ) is controlled based on:

$$m_{DC\#}[k] = v_{bat}[k] + L_{\#A} f_{sw} (i_{DC\#}^*[k] - i_{DC\#}[k]) , \quad (5)$$

where,  $m_{DC\#}$  is the modulator for each DC-DC module (the same for two carriers with a phase-shift of  $180$  degrees),  $L_{\#A}$  is the value of the inductor in each DC-DC module,  $i_{DC\#}^*$  is the current

reference, and  $k$  corresponds to the actual sampling of the digital control algorithm, executed with a frequency ( $f_s$ ) given by:

$$f_s = 2f_{sw} . \quad (6)$$

The current reference is established according to a power algorithm common to all the EV fast charger. The necessary power for the EV battery is dependent on the EV battery voltage and such power is provided by the power grid. By implementing a current control with a fixed value, as the EV battery voltage increases, the power also increases. The algorithm for establishing the current reference is out of the scope of this paper, since it must consider all the power stages, i.e., including the AC-DC and the isolated DC-DC.

### IV. COMPUTATIONAL VALIDATION OF THE MODULAR DC-DC TOPOLOGY

The computational validation, aiming to support the main contributions of the paper, was performed with a complete model implemented in PSIM, both in terms of the power converters (e.g., IGBTs, passive filters, and a simple battery model) and control systems using C language. Table I presents the main parameters considered in the simulation model. In an industrial design such parameters can be adapted to be in accordance with proper standards, e.g., by adapting the number of modules for different levels of currents. Fig. 3 shows the current in the output side ( $i_{bat}$ ) for a maximum value of  $300$  A, which corresponds to a current of  $100$  A in each individual DC-DC module ( $i_{DC1}, i_{DC2}, i_{DC3}$ ). The obtained output current ( $i_{bat}$ ) corresponds to the reference current, which is much more visible in Fig. 4. In Fig. 4 is also possible to visualize the ripple of such output current ( $i_{bat}$ ), as well as the frequency of such ripple. As expected, due to the proposed current control and modulation technique, the frequency presents a value higher six times, i.e.,  $120$  kHz, exhibiting a key feature of the proposed modular architecture and control.

A detail of the voltage obtained in each individual DC-DC module is presented in Fig. 5. In this simulation case, since it was considered an input voltage in each DC-DC module of  $800$  V

TABLE I. MAIN PARAMETERS CONSIDERED IN THE SIMULATION MODEL

| parameter              | value      | unit    |
|------------------------|------------|---------|
| sampling frequency     | 40         | kHz     |
| switching frequency    | 20         | kHz     |
| $L_{\{1,2\}\{A,B,C\}}$ | 50         | $\mu$ H |
| current per module     | 100        | A       |
| output voltage         | 300 to 600 | V       |
| input voltage          | 400 + 400  | V       |

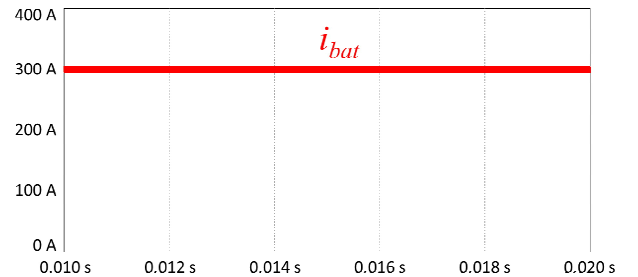


Fig. 3. Results showing the steady-state current in the EV battery ( $i_{bat}$ ), i.e., the combined output current of all the DC-DC power modules (each one operating with a current of  $100$  A).

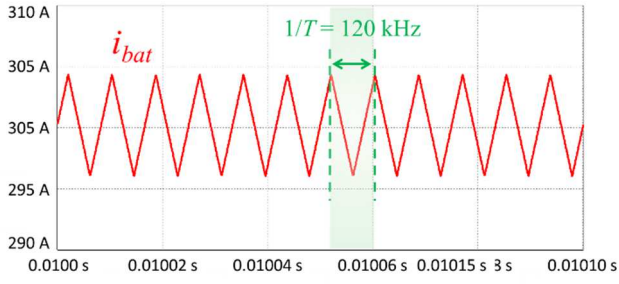


Fig. 4. Results showing the steady-state current in the EV battery ( $i_{bat}$ ), i.e., the combined output current of all the DC-DC power modules, demonstrating the interleaved-based operation, resulting in a ripple with a frequency six times higher than the switching frequency.

and an output voltage of 600 V ( $v_{bat}$ ), then the obtained voltage obtained in each individual DC-DC module is situated between 400 V and 800 V (this voltage is measured between  $x$  and  $z$ , as highlighted in Fig. 2). This variation is achieved since the output voltage ( $v_{bat}$ ) is between such values. By adjusting the input and output voltage values, the obtained voltage will be situated between 0 and 400 V, or between 400 V and 800 V. In addition, the obtained voltages of all the three DC-DC modules presents a phase-shift between them, with a value of 120 degrees. This condition is indispensable to get an output current with a low current ripple and with a higher frequency than the switching frequency presented in each individual DC-DC module.

As an exemplificative case for one of the DC-DC modules, Fig. 6 shows the voltage in one of the IGBTs ( $v_{s\#A}$ ) and in one of the diodes ( $v_{d\#A}$ ). As presumed, the voltage varies based on the voltage obtained in each DC-DC module, assuming the values of  $v_{dc}/2$  or 0 (i.e., 0 or 400 V), which corresponds to the voltage in the input DC voltage (i.e., from the output of each high-frequency transformer). Obviously, as demonstrated in the theoretical section, the frequency of these signals is in accordance with the switching frequency of the IGBT (20 kHz), corresponding to  $1/6$  the frequency of the ripple presented in the output current ( $i_{bat}$ ).

Fig. 7 shows the current in each DC source regarding specifically the DC-DC module #1 (i.e., the currents on both DC of the split DC-link), according to the ON or OFF state of each IGBT of such DC-DC module. As presented, when both IGBTs  $S_{\#A}$  and  $S_{\#B}$  are ON, both DC currents increases, when IGBT  $S_{\#A}$  is ON and  $S_{\#B}$  is OFF, the current  $i_{\#DCA}$  decreases and the current  $i_{\#DCB}$  is zero, and when IGBT  $S_{\#A}$  is OFF and  $S_{\#B}$  is ON, occurs the contrary, i.e., the current  $i_{\#DCA}$  is zero and the current  $i_{\#DCB}$  decreases. The other situation occurs when both IGBTs  $S_{\#A}$  and  $S_{\#B}$  are OFF, where both DC currents are zero, meaning that the DC-DC module is not operating in any mode.

The sum of the currents  $i_{\#DCA}$  and  $i_{\#DCB}$  presented in Fig. 7, results in the output DC current of each DC-DC module ( $i_{DC\#}$ ). The same operation principle is applied for all the DC-DC modules, as represented in the detail of Fig. 8 for the different current in the input DC side of each DC-DC module. Obviously, as visible, the currents of each DC-DC modules are with a phase shift of 120 degrees, i.e., between the currents  $i_{1DCA}$ ,  $i_{2DCA}$  and  $i_{3DCA}$ , and the same for the currents  $i_{1DCB}$ ,  $i_{2DCB}$  and  $i_{3DCB}$ .

Regarding the modulation, to attain the gate pulse pattern for the different IGBTs of each DC-DC module, are necessary  $3 \times 2$  carriers (i.e., considering the specific case under study of 3 DC-DC modules). Since the IGBTs are controlled with a balanced phase-shift between them, the carriers also present the same phase-shift. This is represented in Fig. 9, where it is also

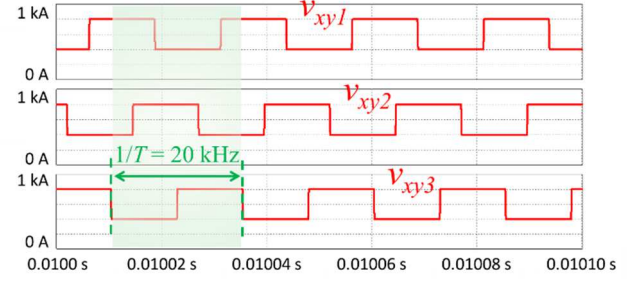


Fig. 5. Results showing the voltage obtained in each DC-DC power module ( $v_{xy1}$ ,  $v_{xy2}$ ,  $v_{xy3}$ ), demonstrating a frequency of 20 kHz and a phase-shift of 120 degrees between them, as well as a voltage varying between 400 V and 800 V (respectively, half and full of the input DC-link voltage).

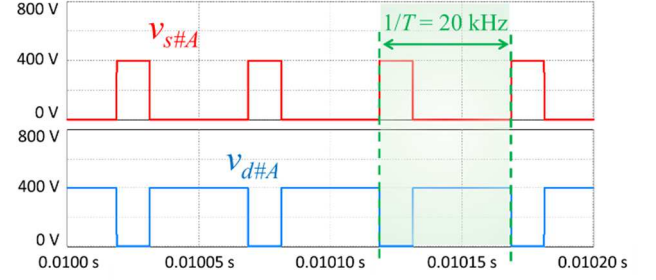


Fig. 6. Results showing the voltage in an IGBT ( $v_{s\#A}$ ) and in a diode ( $v_{d\#A}$ ), demonstrating a switching frequency of 20 kHz and a maximum voltage that corresponds to half of the input DC-link voltage.

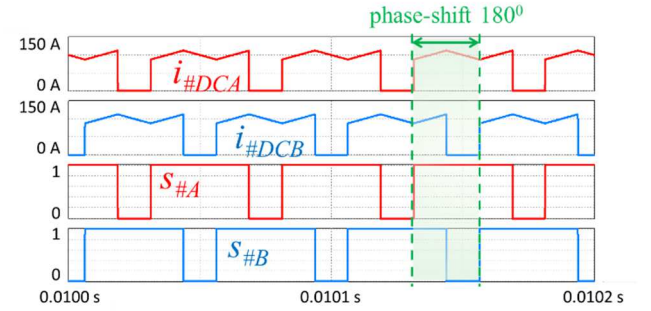


Fig. 7. Results showing the control signals for both IGBTs ( $S_{\#A}$  and  $S_{\#B}$ ) of a DC-DC power module and the current in each half of the input DC-link source ( $i_{\#DCA}$  and  $i_{\#DCB}$ ), demonstrating the phase-shift control of each IGBT for ensuring the interleaved-based operation in each DC-DC power module.

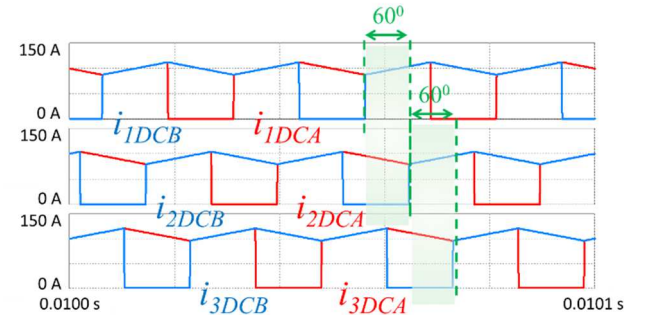


Fig. 8. Results showing the current in each half of the input DC-link source ( $i_{1DCA}$ ,  $i_{1DCB}$ ,  $i_{2DCA}$ ,  $i_{2DCB}$ ,  $i_{3DCA}$ ,  $i_{3DCB}$ ) for each DC-DC power module, demonstrating the phase-shift of 60 degrees between modules (i.e., independently of the phase-shift of 180 degrees internally in the control of each DC-DC power module).

possible to visualize the example of the IGBT gate control for the DC-DC module #1. The IGBTs can be turned ON at the same time or can be ON and OFF in alternative way, but they are never OFF at the same time (i.e., situation that corresponds to

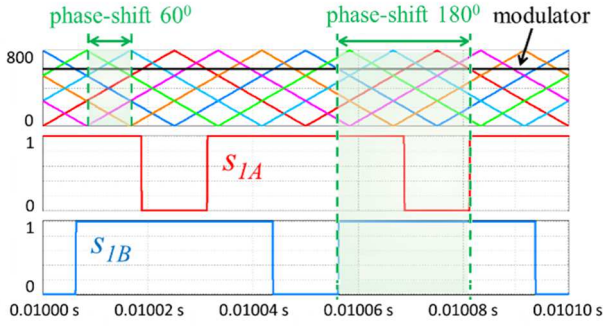


Fig. 9. Results showing all the carriers with a phase-shift of 60 degrees between them, the same modulator, and, as example, the control signals for the IGBTs  $S_{1A}$  and  $S_{1B}$ , demonstrating the phase-shift control of each IGBT for ensuring the interleaved-based operation in each DC-DC power module.

disconnect a DC-DC module). Moreover, it is visible that the reference (modulator) is the same for comparing with all the carriers, i.e., in this case it is considered that all the DC-DC modules are operating with the same value of power. If considering the operation of the DC-DC modules with different values of power (e.g., due to unexpected failures or due to specific control strategies), therefore, of course, different references must be considered for each DC-DC module.

In contrast with the previous cases, where a steady-state operation was validated and analyzed, Fig. 10 shows a particular case of operation in transient-state. Such scenario of operation was considered not for changing the operating power equality for all DC-DC modules, but only changing the operating power of one DC-DC module. This case permits to validate two different points: (i) the modularity of the proposed solution, showing that the operation of the DC-DC modules is individual controlled in terms of current control (but, of course, it is necessary to identify how many DC-DC modules are operating, e.g., to define the phase-shift between the carriers); (ii) the current control in the DC-DC module, quickly adjusting the controlled current to the new variable (e.g., it can be useful in a case of a failure of a DC-DC module or in for reducing the operating power in a case of overheating a DC-DC module). Fig. 10 shows the current in each individual DC-DC module, where the current in the DC-DC module #2 ( $i_{DC2}$ ) was abruptly reduced to half (i.e., from 100 A to 50 A), while the other DC-DC modules continue with the normal current operation (i.e., with a fixed current of 100 A for both  $i_{DC1}$  and  $i_{DC3}$ ). Obviously, since one of the DC-DC modules reduced its current operation, the resultant output current ( $i_{bat}$ ) is also affected in conformity. Nevertheless, a strategy for compensating this reduction can be adopted for ensuring that the output current ( $i_{bat}$ ) remains the same, meaning that the other currents ( $i_{DC1}$ ,  $i_{DC3}$ ) must increase. This control strategy can be adopted just if necessary and, most important, if the hardware permits such an increase in the current.

In Fig. 5 is presented a situation when the voltage obtained in each DC-DC modules is between 400 V and 800 V, since the output voltage ( $v_{bat}$ ) is greater than half of the DC-link voltage in each module, i.e., the output voltage ( $v_{bat}$ ) has a value of 600 V. However, if the output voltage ( $v_{bat}$ ) changes, the obtained voltage in each module also changes, as presented in Fig. 11, where the output voltage is 300 V, forcing each DC-DC module to operate with a voltage between 0 and 400 V. This is valid, e.g., when charging the battery with constant current, since the voltage will increase. As visible, the phase-shift and frequency of each voltage is not affected, remaining the same, respectively, 120 degrees and 20 kHz.



Fig. 10. Results showing the transient-state current in the EV battery ( $i_{bat}$ ), resulted from the sum of the output current of all the DC-DC power modules ( $i_{DC1}$ ,  $i_{DC2}$ , and  $i_{DC3}$ ), demonstrating that each DC-DC power module is controlled individually, in this case, with a sudden variation of the current  $i_{DC2}$ , forcing to reduce also the current in the EV battery ( $i_{bat}$ ).

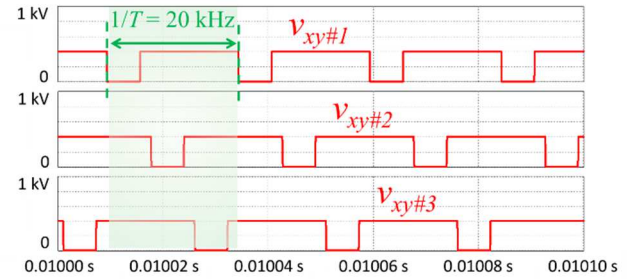


Fig. 11. Results showing the voltage obtained in each DC-DC power module ( $v_{xy\#1}$ ,  $v_{xy\#2}$ ,  $v_{xy\#3}$ ), demonstrating a frequency of 20 kHz and a phase-shift of 120 degrees between them, as well as a voltage varying between 0 V and 400 V (respectively, zero and half of the input DC-link voltage), which is caused by the variation of the voltage in the EV battery (i.e., when it is higher than half of the input DC-link voltage).

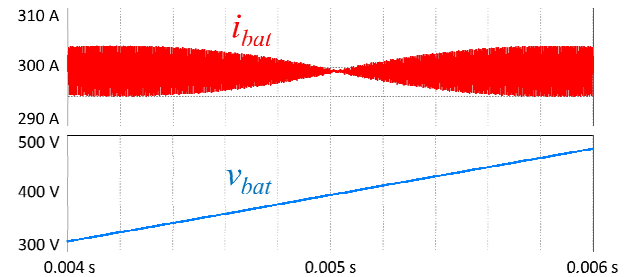


Fig. 12. Results showing the current and the voltage in the EV battery ( $i_{bat}$  and  $v_{bat}$ ), demonstrating that the ripple in the current is eliminated when the voltage in the EV battery ( $v_{bat}$ ) corresponds to half of the input DC-link voltage.

Aligned with the result reported in Fig. 11, in Fig. 12 is presented a situation that demonstrates the relation between the ripple of the output current ( $i_{bat}$ ) and the output voltage ( $v_{bat}$ ), assuming a fixed value of the input voltage. Although the ripple of the output current presents the same frequency, it is identified that it has a variable amplitude in conformity with the output voltage ( $v_{bat}$ ). More specifically, when the output voltage reaches half of the DC-link voltage in the input of a DC-DC module, then the output current ( $i_{bat}$ ) has not ripple (i.e., ripple-free working point; see [20]). The amplitude of the ripple converges to zero when the output voltage converges to 400 V, increasing again to a steady value while the output voltage ( $v_{bat}$ ) increases. This case is of particular interest since, with a strategic control algorithm, it is possible to adjust the voltage in both sides aiming to reduce the output current ripple.

## V. CONCLUSIONS

The diffusion of electric mobility in different sectors and countries maintains a systematic grow, which is only possible due to the advances of numerous technologies. In such scope of EV charging technologies, a modular interleaved-based DC-DC converter topology for EV fast chargers is proposed in this paper. It is based on DC-DC power modules with output power combined in parallel (maximum 100 A per module), while the diverse inputs are totally individual (400 V +400 V), which can be an interesting possibility for interfacing an isolated DC-DC power conversion stage. For controlling the modular interleaved-based DC-DC topology, a modulation scheme is proposed, and it is explained how it can be explored when increasing the number of DC-DC modules for  $n$ , linked between them. With the proposed modulation scheme, any linear current control strategy can be applied, always obtaining a fixed-switching frequency (20 kHz). The achieved results show that the proposed modular DC-DC converter topology operates in interleaved-based strategy, ensuring a split and balanced (or not) current among the DC-DC modules. Moreover, the advantages of reducing the ripple in the output current is also demonstrated (e.g., null ripple for a battery voltage of 400 V). The validation was realized for three DC-DC modules, considering critical conditions of operation, where the correct operation for all conditions is highlighted. A comparison between the obtained results with other existing topologies aiming to verify in more detail the superiority of this paper can be considered for a future extension of this work.

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