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Design of a bi-directional DC/DC converter for EV chargers oriented to V2G applications

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Abstract. In order to address the problems caused by climate change, electric vehicles have gained international attention in recent years. Furthermore, special attention is being paid to the Vehicle to Grid (V2G) services that this technology can provide. In this context, the development of bi-directional chargers is gaining importance. Taking all this into consideration, in this work a simple and easy-to-implement solution of the DC/DC stage of a bidirectional electronic charger that allows the integration of EVs in V2G applications has been designed and validated through simulation.

Key words. Bidirectional charger, V2G, Electric Vehicle, Grid Support, Control Strategy.

1. Introduction

In recent years, climate change has prompted the development of alternative and more sustainable technologies to those that have traditionally been used. In the process of decarbonisation and electrification of the energy sector, Electric Vehicles (EVs) are gaining importance [1]. It is believed to be a key technology that will act, together with Renewable Energies (RES), as the core of the energy transition and the energy model of the future. Proof of this is the evolution of the EV fleet globally, which has grown from 2 million units in 2016 to more than 10 million in 2020 [2].

With respect to EVs, one of the other advantages that are recently gaining relevance is the capacity to provide auxiliary services to the electrical grid, i.e., Vehicle to Grid (V2G) services [3]. These services are seen as one of the possible solutions to the technical problems of a high penetration of renewable energies in the electricity system [4], [5]. This is possible because EVs are parked most of the time (around 96%) [6]. Therefore, during the time the EV is parked, it can be providing V2G services to the grid, as long as it is charged for when the owner needs to use the vehicle.

But for this technology to advance, it is essential that the development of power electronics, in particular the development of bi-directional EV chargers and their control [7]. These chargers are normally made up of two stages, a DC/DC stage that goes from the batteries to the DC bus and another DC/AC stage that goes from the DC bus to the grid.

Considering all of the above mentioned, the aim of this work is to design and validate through simulation a simple and easy-to-implement solution of a bidirectional electronic charger that allows the integration of EVs in V2G applications. Thus, the converter model developed should allow the evaluation of optimisation strategies for the charging and discharging processes of the EV battery. In addition, it should be noted that the work developed comprises only the DC/DC stage. In this sense, the electronic converter to be developed will only contemplate the management of DC power flows between the battery and a DC-AC converter that will connect the converter to be developed with the electrical grid.

Finally, this work does not aim to develop optimal recharging strategies. Thus, the scope of the work only comprises the development of a converter that will be part of a larger system, on which optimisation strategies in the V2G domain can be evaluated. However, despite not considering optimal recharging strategies, this work also focuses on the development of control strategies for the converter, so as to facilitate the subsequent evaluation of optimal strategies to be applied in future developments. In this sense, the development of the control strategies will consider the integration and interoperability of the converter to be developed with the EV battery subsystem and the DC-AC converter that will finally integrate the EV with the grid.

2. Bidirectional DC/DC converter and the control strategy

The adopted solution contemplates the development of a converter that manages the DC power flows between the battery and the DC-AC converter. The converter chosen is a non-isolated four-switch bidirectional Buck-Boost DC-DC converter due to its simplicity, and because it does not require the use of a transformer and allows the quick and easy management of power flows between the battery and the grid. It also allows easy implementation and validation of optimisation strategies for EV charging in the V2G domain. Moreover, it is a suitable solution when there is a wide input and output voltage variation, such as in the case of charging an electric battery, whose voltage varies widely depending on its state of charge.

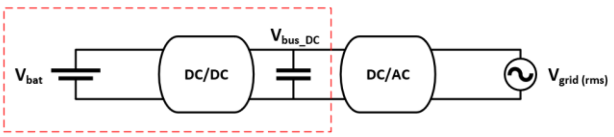

Fig. 1. Schematics of the bidirectional EV charger.

In order to provide the system a more precise control, it has been decided to establish an interchangeable master-slave control strategy between the DC-DC converter and the DC-AC converter. In this sense, during the charging process, the DC-DC converter will take the role of master by regulating the charging current, whose reference will be established through the optimal charging strategies to be evaluated. Thus, the DC bus voltage between the DC-DC converter and the DC-AC converter will be controlled by the DC-AC converter operating as a slave. During the discharge processes (grid support), the roles of the converters will be exchanged, so that the DC-AC converter will be the master, in charge of regulating the current injected into the grid (determined by the setpoints generated by the optimal recharge strategies to be evaluated) and the DC bus voltage will be managed by the DC-DC converter, which will take on the role of slave.

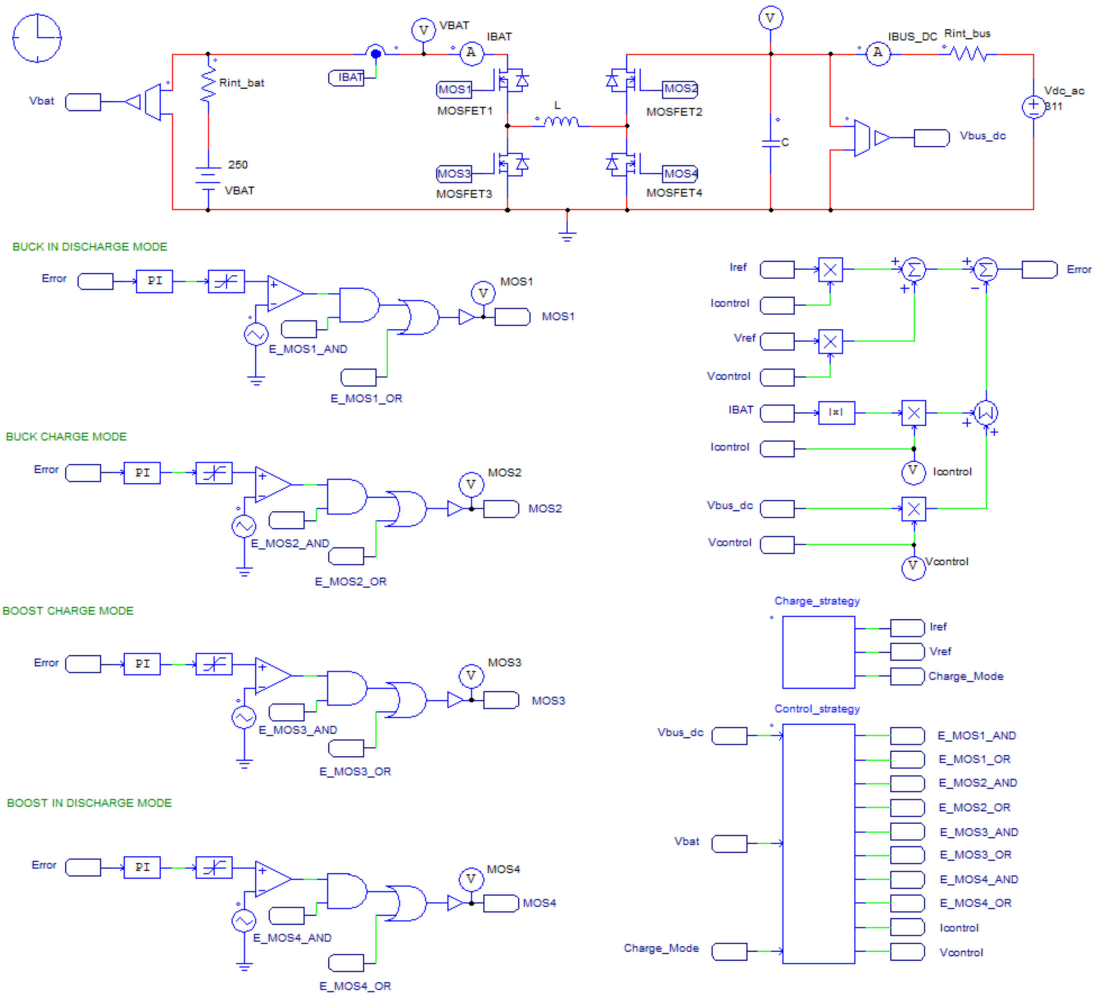

Fig. 2. Implemented system.

Table I. – Converter's operation mode, voltage comparation and each MOSFET's role.

Operation	**Voltage comparation**	**Topology**	**S1**	**S2**	**S3**	**S4**
Charge	$V_{batt} < V_{bus\_DC}$	Buck	ON	D	OFF	OFF
Charge	$V_{batt} > V_{bus\_DC}$	Boost	OFF	ON	D	OFF
Discharge	$V_{batt} < V_{bus\_DC}$	Boost	ON	OFF	OFF	D
Discharge	$V_{batt} > V_{bus\_DC}$	Buck	D	ON	OFF	OFF

Likewise, for each charge and discharge operating mode, depending on the DC bus voltage and battery voltage, the converter will have to modify its configuration to operate in buck mode or boost mode. For this purpose, a control block will be the responsible for determining which semiconductors will have to enter in cut-off or saturation mode, as well as which semiconductor will be in charge of managing the converter's duty cycle. The control strategy for both charging and discharging is based on PI control loops and Pulse Width Modulation (PWM) technique to control the duty cycle of each MOSFET. During charging, the control loop will be a current loop while during discharging it will be a voltage loop.

3. Results and discussion

In order to validate the correct operation of the converter, six different simulation cases have been set up. These six simulations can be divided into two groups.

The first group consists of four simulations showing the charging or discharging of the converter, with variations in the current and voltage references, for the Buck or Boost modes. The purpose of these simulations is to check the correct activation of each MOSFET for each operating mode (charge and discharge, Buck and Boost), as well as to check that the converter control loops are able to properly follow the voltage reference setpoints during discharge and the current setpoints during battery charging.

The second one, with the idea of making it more realistic, by means of a simple code, a charging process followed by a discharging process has been simulated (emulating a possible participation in the auxiliary grid services), forcing the converter to operate in Buck mode during charging and Boost mode during discharging (manually adjusting the battery voltage to 250 V during charging and discharging, and to 311 V the DC bus voltage during charging). The same simulation has been repeated, but this time forcing the converter to operate in Boost mode during charging and Buck mode during discharging (manually setting the battery voltage to 420 V during charging and discharging and the DC bus voltage to 311 V during charging).

To simplify the simulations, ideal voltage sources with series resistors have been used to emulate the battery and DC bus voltage, for the cases where the latter is supposed to be regulated through the DC-AC converter (discharge mode). The ideal voltages have been used in order to simplify the simulations, as they have no particular influence on this design, since the objective is to regulate the voltage at the discharge and the current at the charge. In addition, the most restrictive cases, when the battery is fully charged and discharged, have been simulated.

A. *Buck in charge mode*

For this first case, as the battery needs to be charged, the charge command is set to 1 (Charge_Mode=1). In addition, MOSFET 1 must be in ON mode, MOSFET 2 switching, and MOSFETs 3 and 4 must be off. In this mode of operation, the converter operates in current control mode, receiving the current control setpoint from the block emulating the optimal recharge strategy. An initial charge setpoint of 2 A has been set, then to 6 A after 5 s, and the DC bus voltage has been set to 311 V (emulating that the DC-AC converter adjusts the voltage level to that value). Also, to force the converter to work in Buck mode, the battery voltage has been set to 250 V.

Figure 3 shows that the current through the battery is perfectly in line with the reference setpoint, obtaining a critically damped response and reaching steady state in less than 250 ms. As for the voltage level on the DC bus, there is a small drop due to the voltage drop in the series resistor that connects to the voltage source, which emulates the voltage that would be set by the DC-AC converter. A current ripple of 0.1 A peak-to-peak (5 %) has been obtained.

B. *Boost in charge mode*

In this second case, as the battery charge is still being analysed, the charge setpoint will be equal to 1 again (Charge_Mode=1). As this is now in Boost mode, MOSFET 1 and 4 must be switched off, MOSFET 2 in ON mode and MOSFET 3 switching. As in the previous case, an initial current setpoint of 2 A has been set and subsequently adjusted to 6 A at 5 s. Also, to force the converter to operate in Boost mode, the battery voltage has been set to 420 V.

As in the previous case, here too the control is performed by means of the closed current loop. Figure 4 shows that the converter follows the set current setpoints. However, in this case the converter operates in discontinuous mode. This is because the calculated inductance is perfectly matched for Buck mode operation, but not for Boost mode. There is a voltage variation on the DC bus when the current setpoint is changed because the voltage at the input of the converter is not really being controlled, which in the real application should be done by the DC-AC converter.

C. *Buck in discharge mode*

For the next two cases, as it is the battery discharge that is to be analysed, the charge setpoint should be set to 0 (Charge_Mode=0). In this first case, to analyse the Buck mode, MOSFET 1 should be switching, MOSFET 2 in ON mode, and MOSFETs 3 and 4 in OFF mode.

Unlike in the two charging cases, the battery discharge is performed by voltage control, so that the converter operates by regulating the DC bus voltage. That is why, as shown in Figure 5, the current control signal is equal to 0, and the voltage control signal is equal to 1. To force the converter to buck mode, the battery voltage level has been set at 420 V, and an initial voltage reference of 311 V has been set, and after 5 s it is set at 315 V, and it can be seen how the converter correctly follows this reference. It can be seen how in this mode the converter works in discontinuous mode. The voltage ripple value obtained for this case was 0.2 V peak-to-peak (0.06 %).

D. *Boost in discharge mode*

In this case, as the battery is to be discharged, the charge setpoint must be set to 0 (Charge_Mode=0). In addition, to ensure that the converter operates as Boost, MOSFET 1 will be in ON mode, MOSFETs 2 and 3 in OFF mode and, finally, MOSFET 4 must be switching.

Here again, what was analysed in the previous case (Buck in discharge mode) is also fulfilled. As the control is done by voltage instead of current, the current control signal is equal to 0 and the voltage control signal is equal to 1 (Figure 6). To force the converter to operate in Boost mode, the battery voltage level has been set at 250 V, and an initial voltage reference of 311 V has been set, and after 5 s it is set at 315 V. It can be seen how the converter correctly follows this reference.

E. *Charge and discharge of the battery (V_{bat}=250 V)*

In this first configuration the battery voltage is equal to 250V, so the converter will act in Buck mode during charging. During the first 5 seconds of simulation, MOSFET 1 is in ON mode, MOSFET 2 is switching, and MOSFETs 3 and 4 are in OFF mode.

The converter operates in current mode, with the variable Icontrol taking the value 1 and Vcontrol taking the value 0, thus enabling the current control loops.

On the other hand, once the 5 seconds of simulation have elapsed, the converter switches to discharge mode by setting Charge_Mode=0. In this operating mode, MOSFETs 1 and 3 do not change their previous state (MOSFET 1 ON mode, MOSFET 3 OFF mode), but MOSFETs 2 and 4 do. MOSFET 2, which was switching before, becomes 0, and MOSFET 4 switches to the opposite; it was at 0 and now switches. With this new configuration, the converter will be operating in Boost mode.

Figure 7 shows that the control now switches from controlling the battery charging current (while the battery is charging) to controlling the DC bus voltage (while the battery is discharging).In addition, at that precise moment, the battery current goes from -5A to 5A, and the voltage rises from about 309V (due to losses in the DC bus resistor) to 315V, which is the voltage reference. Also, a voltage and current peak is seen during the change of converter topology, from Buck in charge mode to Boost in discharge mode.

F. *Charge and discharge of the battery (V_{bat}=420 V)*

Finally, in this last simulation, a value of 420V is set on the battery to force the converter to operate in Boost mode during the charge. Thus, during the first 5 seconds of simulation, MOSFET 1 and 4 will be in OFF mode, MOSFET 2 in ON mode and, MOSFET 3 will be switching. Consequently, the converter will be operating in Boost mode.

In the first 5 seconds of simulation, the current control is performed (Charge_Mode=1), so by setting a current of 5A as a reference, the voltage that will be reached will be a little lower than 311V (due to losses in the resistor).

After 5 seconds of simulation, the charge control signal is modified (Charge_Mode=0), so the converter will start to regulate the DC bus voltage during battery discharge, so the configuration of the MOSFETs changes again. MOSFET 1 is now switching, and MOSFET 3 is now in OFF mode, while MOSFETs 2 and 4 do not change state (MOSFET 2 ON and MOSFET 4 OFF). With this new configuration, the converter is now in Buck mode.

Finally, as in the previous case, Figure 8 shows how, depending on the load mode setpoint, the control switches from current control mode to voltage control mode. Thus, the current goes from -5A (charging) to approximately 2A (discharging), while the DC bus voltage takes on the value established in the voltage control reference, i.e. 315V. It can be seen how in this case, when switching from charging in Buck mode to discharging in Boost mode, neither the current peaks in the battery nor the voltage peaks on the DC bus are as severe.

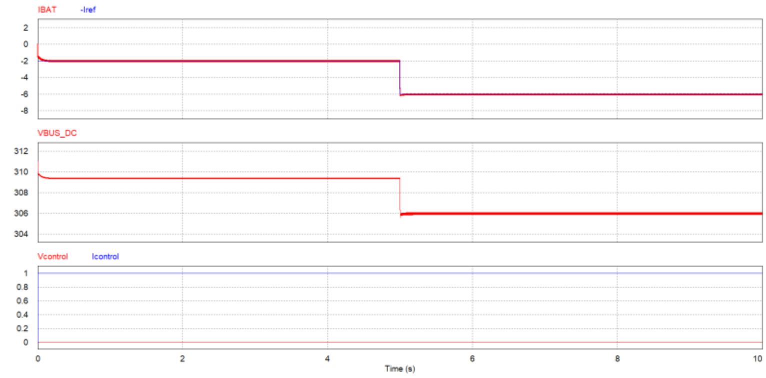

Fig. 3. Simulation results of the buck converter in charging mode (currents, voltages and control).

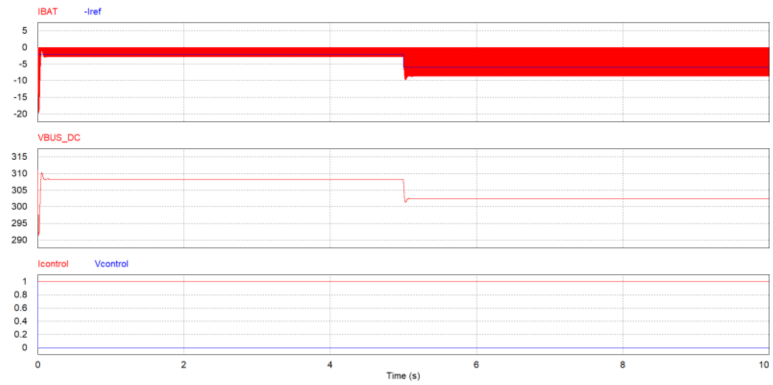

Fig. 4. Simulation results of the boost converter in charging mode (currents, voltages and control).

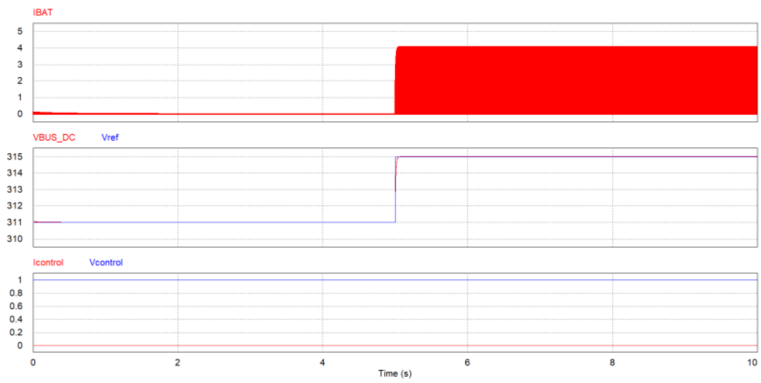

Fig. 5. Simulation results of the buck converter in discharging mode (currents, voltages and control).

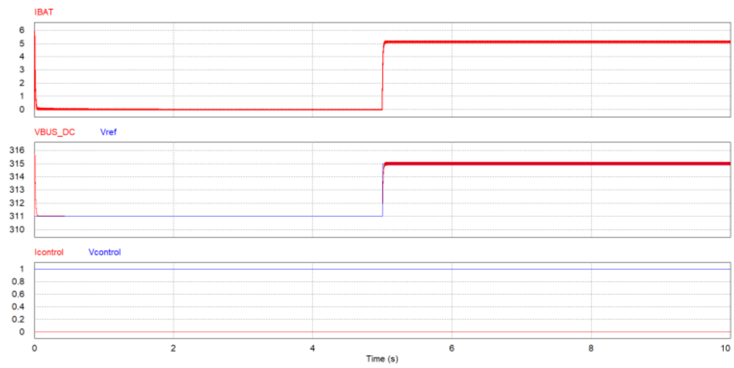

Fig. 6. Simulation results of the boost converter in discharging mode (currents, voltages and control).

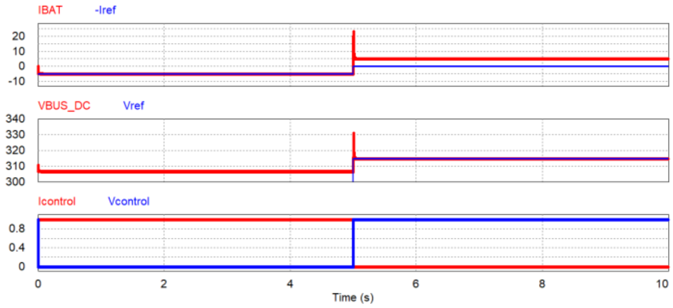

Fig. 7. Battery current, DC bus voltage and control signals during charging and discharging of the battery (V_{bat}=250 V).

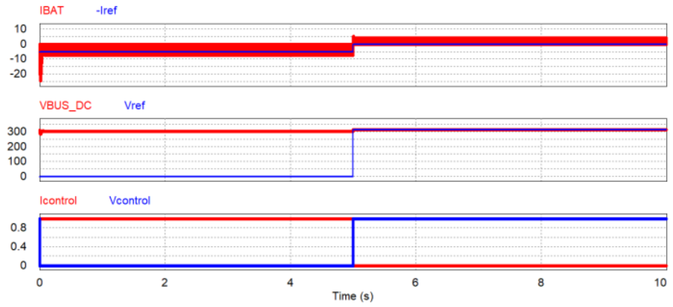

Fig. 8. Battery current, DC bus voltage and control signals during charging and discharging of the battery (V_{bat}=420 V).

4. Conclusion

In this work, the first stage of a bidirectional charger for V2G applications for electric vehicles has been designed and validated. With different simulations carried out in PSIM, the correct operation of the developed converter has been verified, although it should be noted that in order to be able to analyse the battery discharge mode more realistically, the bidirectional DC-AC converter would have to be integrated into the current circuit. This would therefore remain an issue for future development.

Furthermore, it has been seen that, in a real application, it would be necessary to integrate a snubber circuit to reduce the voltage peak that occurs when the control mode is changed and the battery is switched from charging to discharging.

Finally, in order to guarantee better operation of the converter developed in all operating modes (Buck and Boost in charge and discharge), it is proposed to use two different capacitors and two different inductances, so that, depending on the operating mode, the converter topology is modified to use one component or the other.

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