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Review of V2G and G2V Bidirectional Converter

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Abstract: *In response to climate change, which is caused by the increasing pollution of the environment and leads to the deterioration of human health, future electricity generations should reduce reliance on fossil fuels by growing the use of clean and renewable energy generation sources and by using clean vehicle technologies. Battery storage systems have been recognized as one of the most promising approaches for supporting the renewable energy generation sources and cleanly powering vehicles instead of burning gasoline and diesel fuel. However, the cost of batteries is still a prominent barrier for their use in stationery and traction applications. As a rule, the cost of batteries can be decreased by lowering material costs, enhancing process efficiencies, and increasing production volume. Another more effective solution is called Vehicle-to-grid (V2G) application. In V2G application, the battery system can be used to support the grid services, whereas the battery is still in the vehicle. To make a battery system economically viable for V2G/G2V applications, an effective power-electronics converter should be selected as well. This converter should be supported by an advanced control strategy. Therefore, this article provides a detailed technical assessment and review of V2G/G2V concepts, in conjunction with various power-electronics converter topologies. In this paper, modeling and detailed control strategies are fully designed and investigated in terms of dynamic response and harmonics. Furthermore, an extensive design and analysis of charging systems for low-duty/high-duty vehicles are also presented.*

Keywords: electric vehicle; Grid-to-Vehicle (G2V); Vehicle-to-grid (V2G); control strategy; charging methodologies; power-electronic converters

I. INTRODUCTION

Nowadays, there exist a lot of concerns related to the pollution of the air, the reliance on fossil fuels, energy dependence, climate change, and the increase of the energy costs. The major efforts to solve these problems are centered in the electricity generation sector, with the deployment of renewable energies, and with the electrification of transportation [1–3].

The variability of renewable resources is a restraint to their installation. This variability could be mitigated with the use of energy storage systems. Moreover, as recent studies have shown [4], EVs are definitively advantageous over other traditional energy-storage technologies thanks to its easy implementation and being environmentally friendly.

The main characteristic of an EV is that it uses an electric motor rather than an internal-combustion engine for propulsion. Their main components are included in Figure 1. The PEVs carry an on-board storage system and can be recharged from an external source of electricity. PEVs include BEVs, PHEVs, and conversions of conventional vehicles [5]. They are usually divided in 3 groups:

Light duty: which includes passengers' cars and small transports;

Medium duty, such us vans;

Heavy duty, like tracks and buses.

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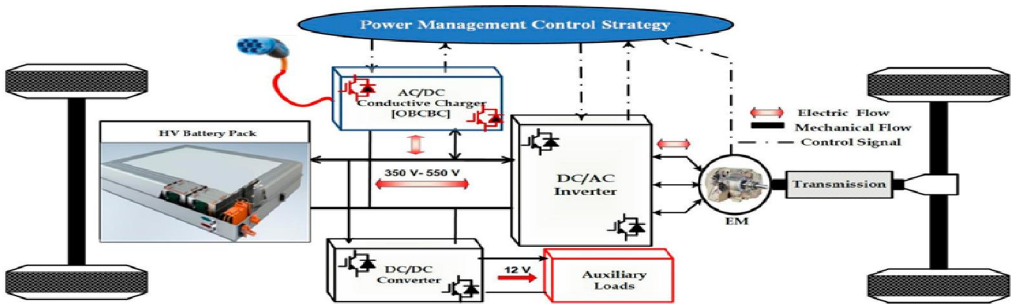

Figure 1. Diagram of the electric vehicle's components.

The main advantages of using EVs are the reduction of CO2 emissions and dependence on fossil-fuels, the higher installation of renewable resources, a better price of energy, the provision of ancillary services, the flattening of the demand curve and theV2G application [5,6].

On the other hand, the use of these systems also carries disadvantages, such us the higher price of the vehicle, the need of charging infrastructure, the overload of the transmission and transportation networks, and safety risks [5,6].

The V2G application consists on having direct power flow between the vehicle and the grid. If effectively controlled and introduced in a smart grid, the V2G application can increase the supply grid efficiency, reliability, stability, and generation dispatch [4]. In addition, it can offer ancillary services, support to the grid operator, load factor improvement, current harmonics reduction, and faster repaid of the storage systems [4,7,8].

Despite its benefits, V2G application is still in the development process. To spread their use, the manufacturers must ensure that the vehicle is charged when the user needs it [9]. On the other hand, it is essential that the electricity grid is not perturbed by the V2G application if the power supplied by the EV does not satisfy the quality requirements imposed by the grid, it cannot be delivered. For this restriction, it is necessary to use a power factor correction (PFC) system, to reduce the current harmonics (respecting the EMC regulation), and to eliminate DC currents so that the grid's transformers are not saturated [10]. A reduction of efficiency and voltage deviations may also be present, produced by the overload of transformers, cables, and feeders [7]. The battery's degradation should be considered as well, since the increase of charging and discharging cycles can reduce its lifespan or life cycle [4]. Furthermore, the bigger is the amount of PEVs connected to the grid, the more severe are the previous problems in the power distribution system [4].

This paper reviews and analyzes the main components of V2G and G2V topologies by emphasizing the benefits offered by such a topology. The main objective of this paper is to demonstrate how both V2G and G2V topologies can be implemented by simulating Four different topologies; two of them correspond to a low-duty vehicles of 3.3 kW (with/without DC/DC converters), while the other two are for Fast Charging and high-duty vehicles of 22 kW (with/without DC/DC converters), using Matlab/Simulink.

Battery Charging Technologies

Conductive vs. Inductive Chargers

The connection between the grid and the vehicle can be either conductive or inductive. Conductive chargers connect the charge inlet to the connector of the EV using a cable, manually plugged in by the driver [11], which can be fed with the three power levels. There exist safety risks in wet and damp conditions, and an easy automation cannot be achieved [12].

On the contrary, the power transfer in an inductive charger is magnetically. This kind of charger comprises two different parts: the grid side in which AC current is taken, rectified and converted to a high frequency [13]; and the secondary side, situated in the vehicle, which consists on an AC/DC converter connected to the battery. At the end of each side, a winding is located forming a transformer through which the power is transmitted, as shown in Figure 2. As both sides of the charger are electrically separated, they can be moved with respect to the other, entailing charging while moving.

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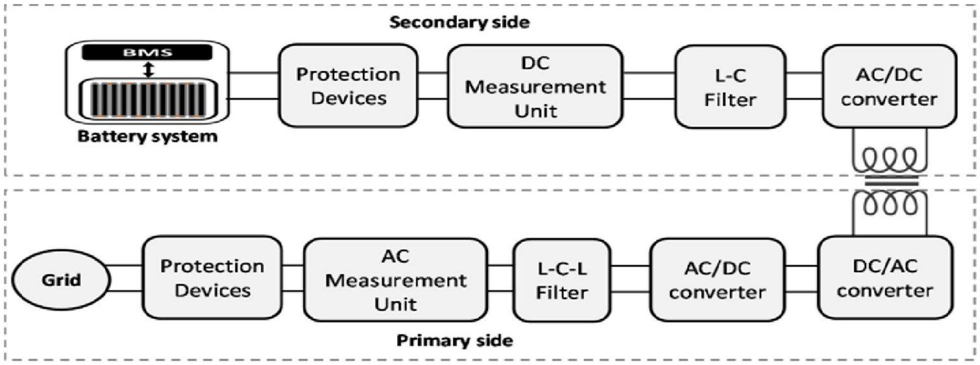

Figure 2. Example of the structure of an Inductive Charger.

The major advantages and disadvantages of these systems are compared in the following Table 1. Figure 3 shows the scores of these chargers in different aspects. In the last years, the main trend is to focus on lower power ratings for inductive charging (because of weight, cost, safety, etc.; and higher power for conductive charging. However, this would mean using two different chargers for a single vehicle, which currently is economically unviable [14].

On-Board vs. Off-Board Chargers

The charger's structure can be included or not in the vehicle, and these chargers receive the name of On-Board and Off-Board chargers, respectively (see Figure 4). The main advantages and disadvantages of the previous types of chargers can be seen in Table 2. Figure 5 shows the scores of these chargers in different aspects, being 0 the worst punctuation and 10 the best.

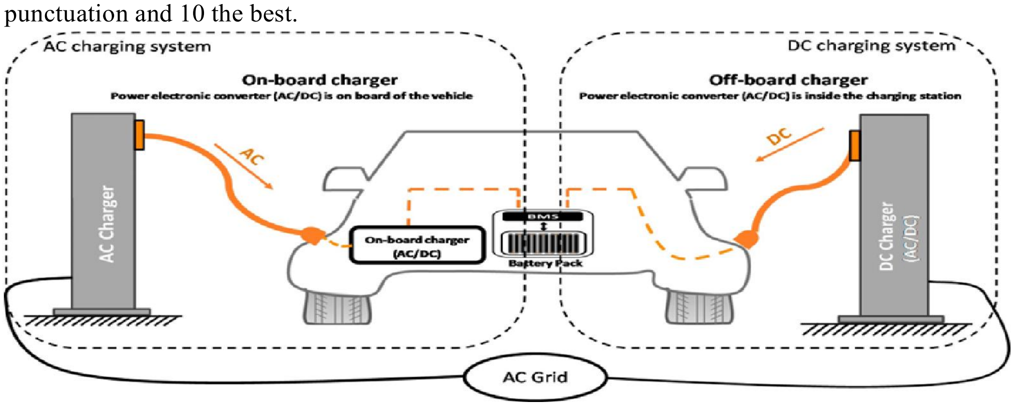

Figure 4. On-board charger versus off-board charger

On-Board chargers are limited to level 1 and 2 (slow charging) because of cost, weight, and space constraints. Their main advantage is their capability to charge the batteries wherever a suitable power source, such as a household outlet [17], is available. This can increase the acceptance of Plug-in Electric Vehicles [9,18]. On-Board chargers used at home usually charge during the night, which has minimal impact on the supply grid [4], and they can facilitate the load level control of power utilities as the electricity demand at night is relatively low [1]. Another considered option for On-Board chargers consists of integrating the battery charger into the electric drive system of the PEV when traction and charging are not simultaneous, as in [4]. In this case, the motor windings serve as filter inductors and the motor inverter is used as a bidirectional AC/DC converter. Consequently, weight, volume and cost are minimized while faster charging (level 2 and 3) can be achieved [17,18]. In addition, these chargers are bi-directional by design [17,19]. However, the control complexity and extra hardware needed are challenges to overcome [11,18]. Off-Board chargers do not have space or weight constraints, and that is why they are capable to operate for fast charging. They take AC power from the grid and transform it to DC power that is then delivered to the vehicle [9,19]. Since the EV must include some power electronics for the traction, an Off-Board charger entails redundant power electronics and thus an extra cost. In addition, fast charging can overload the distribution network because of its high-power demand,

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typically larger than double of a household load [1,20]. Further disadvantages involve the risk of vandalism and extra clutter in an urban environment [4,11].

II. MODELING AND CONTROL OF V2G AND G2V SYSTEMS

The V2G technology can provide numerous benefits to the electricity grid as long as a good control is implemented. It is essential to establish a charging and discharging methodology to control the energy taken or given to the battery. This methodology generates the grid current reference for an internal and faster grid current control loop that establishes the switching patterns for the converter, to control the energy given or taken from the grid. The reference current is synchronized to the grid voltage using a PLL. The block diagram of the control is depicted in Figure 8.

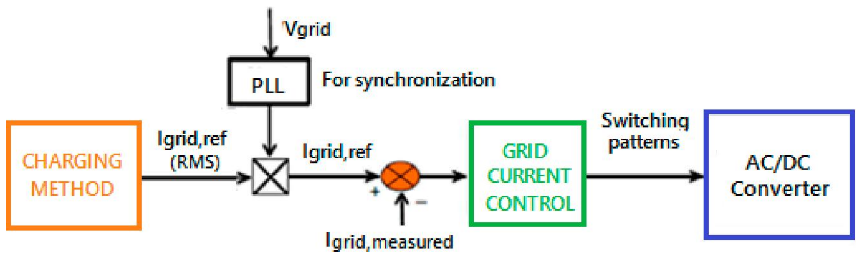

Figure 8. Main control blocks in the system.

The three main charging and discharging methodologies are the following [35–37].

Constant Voltage Charging (CV)

This technique uses the value of the highest voltage (corresponding to the totally charged battery) during the whole charging process. The current is unconstrained, so at the beginning, its value is high, and it decreases as the battery is charging.

Constant Current Charging (CC)

With this methodology, as explained in [35,37], the current applied is constant and the voltage increases while the battery charges. If the battery's impedance is not zero, the battery does not totally charge.

Combined Charging CC-CV

The combined CC-CV charging is the method commonly used for lithium batteries since it enables a complete charging without any overcharge [26]. The first stage of this method, as described in [36], consists on CC charging until the voltage achieves its highest value. Once this value is reached, CV charging is done, maintaining the voltage at its maximum value while the current starts to reduce until it reaches a certain value for which the battery is considered totally charged.

The control blocks and Current and Voltage curves during the implementation of these methodologies are represented in Figure 9.

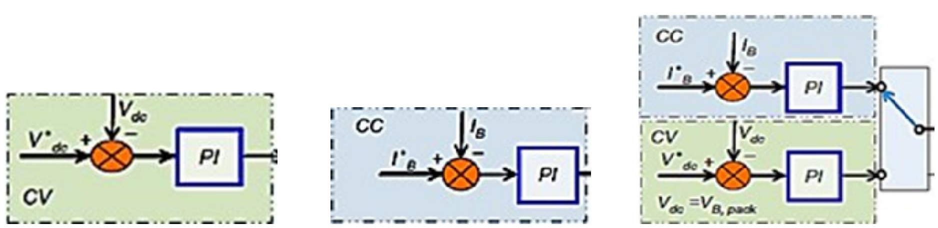

Figure 9. Charging methodologies control blocks and Voltage-Current Curves. (**a**) CV Charging; (**b**) CC Charging; (**c**) CC-CV Charging

On the other hand, the grid current loop can be performed using different control techniques. These techniques are known as Vehicle-to-Grid control strategies and they are responsible for the power flow management for charging (G2V) or discharging (V2G) operating modes [6]. Three different strategies are presented below, and their block diagrams are shown in Figure 10:

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Hysteresis Current Control (HCC)

The hysteresis-band current control is an instantaneous feedback current technique where the switching patterns are generated using a hysteresis band [15,29]. As it has variable switching frequency, the losses are higher than with other strategies [26,38].

Proportional-Integral Control (PIC)

The Proportional-Integral Control uses a PI Controller, whose transfer function is expressed in Equation (1), where K_p and K_i are the proportional and integral gains of the loop. This controller acts continuously, so it is more accurate than the previous method. The switching frequency is constant and equal to the frequency of the triangular signal used for the Pulse-Width-Modulation (PWM). This fact improves the efficiency of the charger. On the other hand, the main problem of this controller is that it cannot do a perfect tracking of the reference.

V2G and G2V Systems for Light-Duty (LD) Vehicles

In this part, V2G and G2V systems for Light-Duty (LD) Vehicles have been analyzed. Two bidirectional single-phase 3.3 kW chargers have been simulated by using Matlab/Simulink (see Figures 14 and 15). Among the available battery technologies, the current two main battery technologies used in EVs are nickel metal-hydride (NiMH) and lithium-ion (Li-ion). Due to the potential of obtaining higher specific energy and energy density, the adoption of Li-ion batteries is expected to grow fast in EVs, particularly in PHEVs and BEVs. Therefore, this research study focused on Li-ion batteries [41]. The first charger consists of an AC/DC converter connected to High Voltage (HV) batteries, is depicted in Figure 14. A Full Bridge has been used for its simplicity and good operation. As reported in [10], this converter is composed by two commutation branches, each comprising two complementary switches, T1–T2 and T3–T4, with which 4 different commutation states can be achieved. The combination of these states provides the desired output voltage wave form. Bipolar modulation is implemented, and the grid inductor is divided in two to minimize the common mode currents [10].

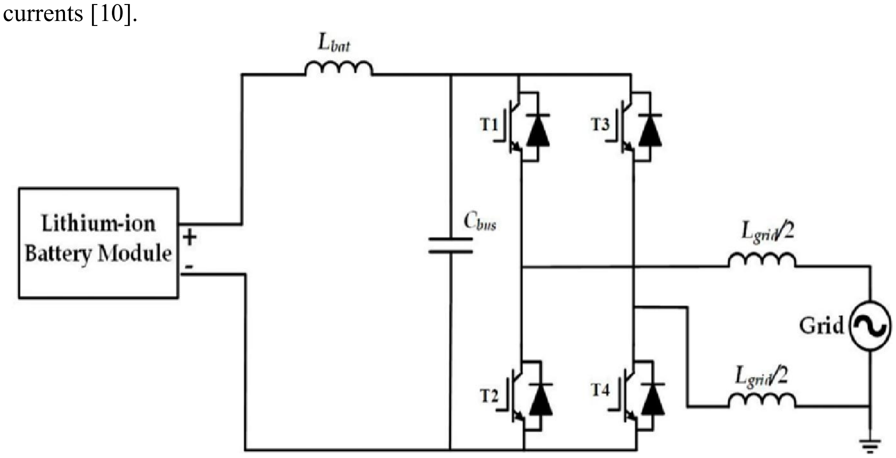

Figure 14. Simulink model of the FB for Light-Duty Vehicles

The second charger counts with the addition of a DC/DC converter to connect to Low Voltage (LV) Batteries. The topology chosen for this DC/DC converter is Two-Quadrant, as seen in Figure 15, and its main parameters are stored in Table 7. In fact, the Two-Quadrant converter consists on having a unidirectional Boost or Buck converter in which the switches are bidirectional, composed by a transistor with a diode in antiparallel, as in [42].

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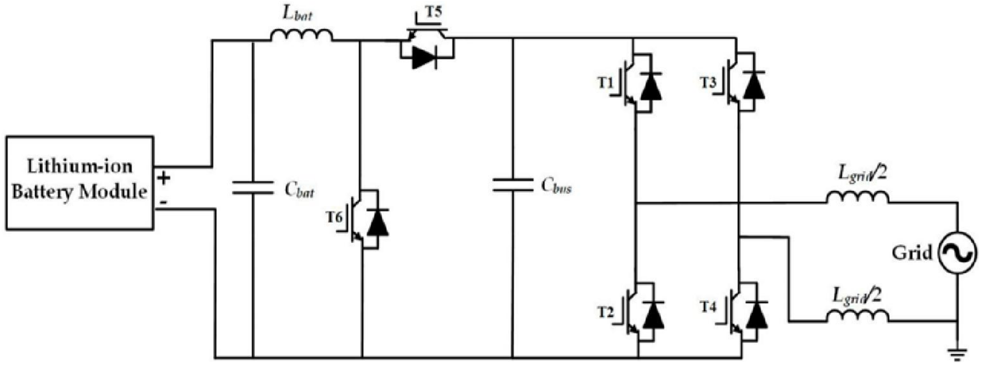

Figure 15. Simulink model of the FB and the Two-Quadrant converter for Light-Duty Vehicles.

V2G and G2V Systems for Heavy-Duty (HD) Vehicles

Afterwards, V2G and G2V systems for Heavy-Duty (HD) Vehicles have been studied, where two bidirectional three-phase 22 kW chargers are simulated by using Matlab/Simulink. As in the previous case, the first topology consists on an AC/DC converter. The chosen topology, as seen in Figure 16, is a Full-Bridge with three commutation branches, as the grid has three phases [43].

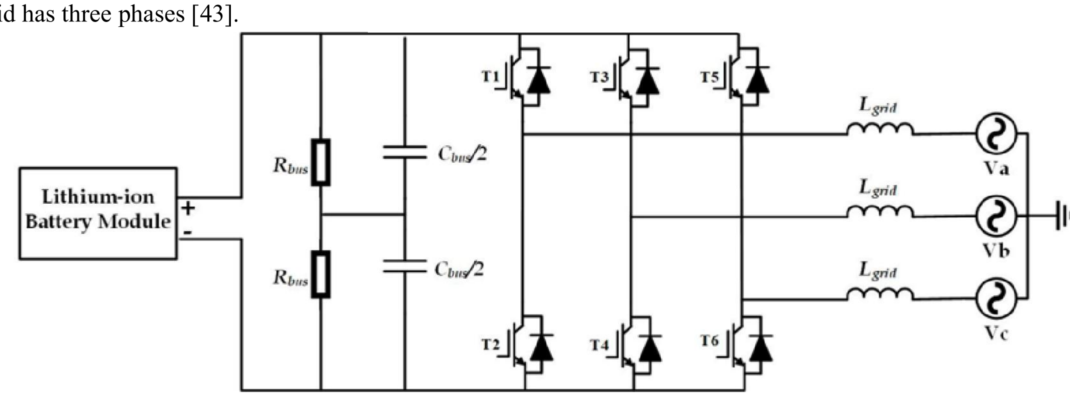

Figure 16. Simulink model of the FB for Heavy-Duty Vehicles.

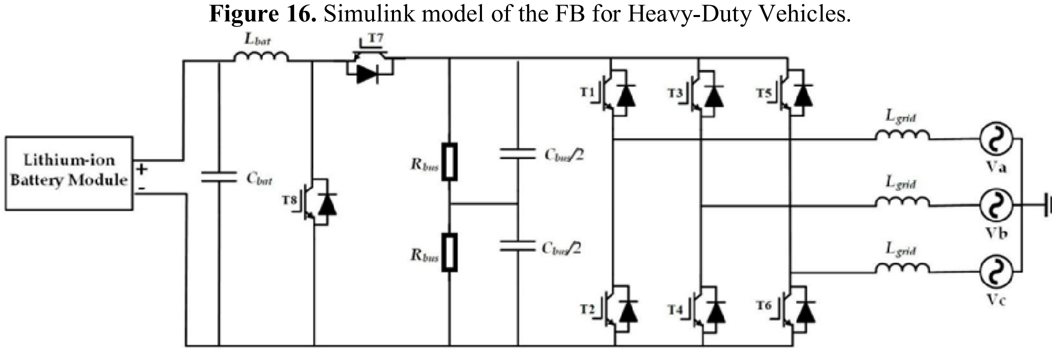

Figure 17. Simulink model of the FB and the Two-Quadrant converter for Heavy-Duty Vehicles.

Comparative Study

A FFT Analysis has been performed for the four topologies developed. The THD of both the AC current and voltage can be seen in Figure 24. In all cases, both G2V and V2G modes have the same level of harmonics. It must be highlighted that the voltage harmonics are reduced to half their value for three-phase, Heavy-Duty systems.

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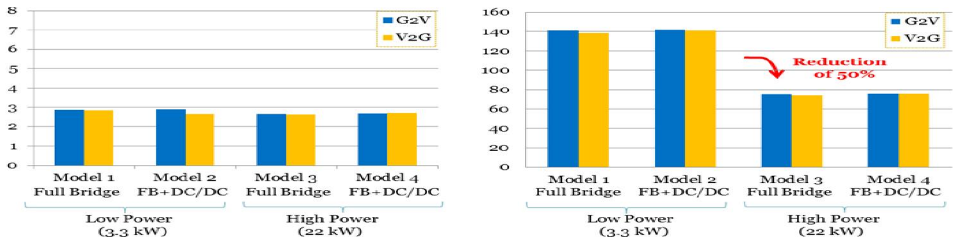

(**a**) (**b**)

Figure 24. Total Harmonic Distortion of the AC waves in the four studied topologies. (**a**) Grid Current THD; (**b**) AC Voltage THD

Finally, a 24-kWh electric vehicle was experimentally analyzed to see the operation of the G2V technology in a real environment. Three different measurements of the State-of-Charge (SoC), Power, Voltage, Current, Power Factor (PF) and Deformation Factor (DF) were taken while the vehicle was charging and they are stored in Table 10. Furthermore, the current and voltage provided at the same time of the measurements are depicted in Figure 25, where signal A is the current and signal B is the voltage.

In all cases, the power factor is capacitive; this means the current leads the voltage. The value of this PF is very good, very close to 1. It can be noted that as the SoC increases, the voltage does too for the NMC battery. This always happens in this kind of electrochemical systems, where the voltage is higher as the system is more charged. Moreover, it has to be noted that for G2V operation, the results from the simulations are very similar to the real ones. Therefore, as positive results were obtained for the V2G operation in the simulation, it can be concluded that the results in a real environment would also be favorable.

III. CONCLUSION

The main research topics of this paper were the design and assessment of four topologies, for both Light-Duty and Heavy-Duty Vehicles, with which the G2V and V2G concepts have been tested. Bipolar modulation was utilized for its easy implementation and almost constant common mode voltage, which enables a transformer-less system. Nevertheless, simulations have shown that the DC currents are very high, so that the installation of a transformer is mandatory to avoid the saturation of the grid's transformers.

Finally, the results of the simulations have been compared to some measurements taken from a real Electric Vehicle while charging. As the parameters and waves obtained are very similar for the G2V mode, it can be concluded that they will also be very similar for the V2G mode. The simulations proved that both G2V and V2G operations have the same perturbation on the electricity grid. Therefore, since G2V is nowadays being implemented, we conclude that the V2G mode could be also implemented and provides its inherent benefits to the grid.

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