

Bidirectional Multilevel Converter for Electric Vehicles

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Abstract — In this paper is presented an H-Bridge Multilevel Converter topology for Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs). The topology of the presented multilevel converter allows the interface between the batteries, the electric motor of the vehicle, and the electrical power grid. Thereby, taking into account that the proposed multilevel converter requires the use of isolated voltage sources, the interface between the batteries and the multilevel converter is evaluated regarding the converter operation as a Battery Management System (BMS), controlling the charging and discharging processes. The interface between the multilevel converter and the electrical power grid is described considering a bidirectional operation. These modes of operation occur during the batteries charging process, denominated as Grid-to-Vehicle (G2V), and during the operation as Vehicle-to-Grid (V2G), that consists in delivering back to the electrical power grid a small amount of the energy stored in the batteries, in accordance with the electrical grid requirements and with the vehicle driver accordance. In both modes of operation, the waveform of the AC current of the electrical power grid is kept sinusoidal with unitary power factor, contributing to maintain a good level of power quality.

Keywords - Multilevel Converter; H-Bridge; Electric Vehicles; Power Quality; Grid-to-Vehicle (G2V); Vehicle-to-Grid (V2G).

I. INTRODUCTION

Nowadays, with the increase of the oil prices and the external energy dependency, mainly in the transportation sector, is extremely important look for alternatives. In the transportation sector a great part of the oil consumption is allocated to the road vehicles. According to the international energy outlook report [1], the transportation sector is going to increase its share in world's total oil consumption by up to 55% by 2030. In this context, driven by the technological development, the electric mobility paradigm is emerging, representing valid alternatives to the Internal Combustion Engines (ICE), such as Electric Vehicles (EVs), plug-in Hybrid Electric Vehicles (PHEVs), and Fuel-Cell Electric Vehicles (FCEVs).

The recent increase in EVs and PHEVs using batteries, as primary or secondary source of energy, represents an effective contribution to the paradigm of the electric mobility in transportation, but this contribution is a little bit limited mainly due of the batteries capacity and their chargers [2]. Thereby, in

these vehicles the batteries are the key of success, and their use should be optimized in accordance with the vehicles powertrain and the electrical power grid. For this goal, in this paper is presented a multilevel converter to be used as interface to the batteries, the electric motor, and the electrical power grid.

The multilevel converters are based on the combination of power semiconductors and voltage sources, achieving an output waveform resulting from the series association of the different voltage sources. The number of output voltage levels is dependent of the number of voltage sources used. Taking into account the final application, the voltage sources can be batteries, capacitors, or renewable energy sources. Increasing the number of output voltage levels involves a greater complexity of the control and command.

Multilevel converters have special importance in the power circuit devices and have been increasingly used in high power applications. When compared with the traditional converters, the multilevel converters has several advantages, mainly, the power losses and the voltage stress on each power semiconductor are more reduced due to series connection, the dv/dt in each semiconductor is more reduced, and the Total Harmonic Distortion (THD) of the output voltage waveform is also more reduced as well the output current. There are several topologies of multilevel converters with special emphasis to the Diode-Clamped, Capacitor-Clamped, and H-Bridge Cascaded Multilevel Converters.

Taking into account that the H-Bridge Multilevel Converter topology requires the use of isolated voltage sources, consequently, it is the ideal solution for EVs and PHEVs applications, due to the large number of batteries used. Other extremely important feature of this multilevel converter is the possibility of operation in bidirectional mode, allowing the batteries charging and discharging processes.

The control of the H-Bridge Multilevel Converter topology is based on the Pulse Width Modulation (PWM) technique. This type of control consists in the comparison of the reference signal (modulator) with multicarrier, and are classified in two groups: Phase-Shifted method (multiple carriers are phase shifted, but with the same amplitude, frequency and offset level), and Carrier-Disposition method (several carriers are used with the same amplitude and frequency, but with different offset levels and can be used different phases) [3] [4].

Thereby, in this paper is analyzed and are shown some computer simulations of a Multilevel H-Bridge Converter topology for EVs and PHEVs, focusing the interface of this multilevel converter with the batteries, the electric motor of the vehicle, and the electrical power grid. Regarding the batteries is assessed the possibility of the converter operation as Battery Management System (BMS), taking into account that this topology of converter uses isolated voltage sources. Related with electric motor are presented some results of their operation controlled by the multilevel converter. The interface with the electrical power grid is described in two ways, the operation of the multilevel converter during the batteries charging process, denominated as Grid-to-Vehicle (G2V), and the operation as Vehicle-to-Grid (V2G) that consist in delivering back to the electrical power grid a small amount of the energy stored in the batteries [5], in accordance with the electrical grid and the vehicle driver. In both modes of operation, the consumed or delivered current, is sinusoidal with unitary power factor, contributing to maintain a good level of power quality [6].

II. BATTERY MANAGEMENT SYSTEM

The main function of a Battery Management Systems (BMS) device is monitor and protects the cells in a battery. The protection consist in preventing the operation of any cell outside its safe operating range, aiming to maximize the battery capacity (balancing the battery's State-of-Charge - SoC) and lifespan (through the State-of-Health - SoH), and should be suited to the requirements of the battery, mainly, taking into account the voltage, current and temperature ratings. Typically, the BMS devices work as interface between the batteries and the charging system. The batteries of the EVs and PHEVs play an important role, and by this reason the BMS should ensure the maximum performance of the vehicle [7][8].

Nevertheless, a BMS device can have different meanings depending on the equipment in question. In some cases it is more than a monitoring system of the main characteristics of the battery, such as voltage, current and temperature ratings, over the charging and discharging processes. Depending of the equipment, they can provide command signals for an external protection circuit and provide other useful data as the historical battery use.

All of the chemical technologies of batteries are susceptible to damages and must be equipped with BMS to estimate the SoC [9][10][11]. However, the batteries based on the lithium are more problematic. There are several chemical technologies of lithium batteries as: Lithium-Ion (Li-Ion), Lithium-Ion Polymer (Li-Pol), Lithium Manganese (LiMn2O4), Lithium Iron Phosphate (LiFePO4), and Lithium Sulphur (Li2S8). Although all are based on lithium, they have different nominal values, and by this reason, there are specific topologies of BMS, so the equipment must be selected carefully. In some specific batteries packs (composed by several batteries cells), the BMS is already incorporated in the cells, however, sometimes these systems should be connected to an external management system, aiming the integration of several batteries packs. Based on the battery environment, and in the data of the charging and discharging process, a BMS is able to calculate several items, such as:

- State-of-Charge (SoC) or Depth-Of-Discharge (DoD) to indicate the charge level of the battery, and State-of-Health (SoH), a measurement of the overall condition of the battery along their lifespan;
- Maximum charge and discharge current and temperatures;
- Internal resistance: dynamic resistance for entire pack or individual cells;
- Total energy delivered and total operating time since their manufacture.

A BMS may report all the above data to an external device, using communication links such as: CAN-bus (typical for automotive environments), direct wiring, serial communications, and wireless communications. In order to maximize the batteries capacity and to prevent the batteries against over-charging they should be balanced in terms of charge. The batteries balancing can be done in three distinct processes:

- Wasting energy from the most charged cells through a dummy load (regulators);
- Reduce the charge current to a sufficiently low level that will not damage the fully charged cells, while less charged cells may continue the charging process;
- Shuffling energy from the most charged cells to the least charged cells. This method, denominated as active balancing, is the most advantageous to the batteries and the most efficient in energy terms.

In order to estimate the SoH and the SoC can be implemented several techniques [12][13]. The main parameters that influence the SoC are the charging and discharging rates, the temperature, the battery SoH, the self-discharge, and the charge and discharge efficiency. The SoC can be measure directly if the discharging current is constant. In this way, the energy provided by the battery is obtained multiplying the voltage and the discharging current along the discharging time. However, this method is not a good solution because, in practical, the discharging current is not constant. Other important aspect to determine the actual SoC with this method is the initial SoC, which should be stored to comparison.

Other method to estimate the SoC is based in the battery voltage. Along the discharge process the battery voltage decrease and consequently the SoC also decreases, and there are a relation between both. However, this method is not satisfactory because, besides the voltage, the SoC is also affected by the temperature, the discharging rate, and the battery SoH (State-of-Health). To obtain a reasonable accuracy of the SoC these parameters should be compensated.

The most common method to estimate the SoC is the Coulomb Counting. Along the batteries charge and discharge processes the current is integrated over time (Ah). In this way, the actual SoC is obtained and is the base of comparison with the energy (VAh) provided by the battery along the discharging process, or the energy delivered to the battery along the charging process. Consequently, if the current vary over time abruptly, this method provides higher accuracy to estimate the SoC.

In this context, with the proper control, the H-Bridge Multilevel Converter can implement all of the main features of a BMS [14]. In this type of multilevel converter the voltage sources are independently and in EVs and PHEVs applications are the batteries. In this way, the contribution of each battery (or a combination of individual cells) to the output voltage of the multilevel converter is individually controlled during the charging and discharging processes, allowing control their SoC in order to preserve their lifespan.

III. MULTILEVEL TOPOLOGY

With the development and growth of microcontrollers (with more processing capabilities and speeds) and power electronic devices mainly in terms of the switching speed, driving higher currents, and supporting large voltage values, it became possible to implement complex multilevel converters.

As referred before, the H-Bridge Cascade Multilevel Converter topology is presented in this paper as the power electronic device to interface the batteries, the electric motor of the vehicle, and the electrical power grid. This multilevel converter is able to synthesize an output voltage with n levels from isolated voltage sources. The quality of the voltage waveform synthesized is dependent of the number of voltage sources used. This multilevel converter topology is one of the most important in the family of multilevel converters, and compared with other topologies (as Diode Clamped and Flying Capacitors) it allows the bidirectional operation, and requires fewer components [15].

In Fig. 1 is shown the topology of the H-Bridge Cascade Multilevel Converter under study in this paper. This 21-level converter uses 10 H-Bridges connected in series, each one capable to synthesize three voltage levels, as shown in Fig. 2. As the main goal of this paper is analyze the behavior of this converter for EVs and PHEVs, the voltage sources are the batteries of the vehicles. However, to facilitate the representation, in the figure were used typical voltage sources.

As mentioned before, the H-Bridge Cascade Multilevel Converter topology allows the bidirectional operation. Thereby, in EVs and PHEVs applications this feature is extremely important, because allows charge the batteries from the electrical power grid (G2V) and deliver back to the electrical power grid a small amount of the energy stored in the batteries (V2G). Besides the possibility of the bidirectional operation, this multilevel topology allows protect the batteries. During the charging process from the electrical power grid (G2V) the protection is obtained through the appropriate control of the H-Bridges, avoiding overcurrents and overvoltages to each individually battery. During this process, each battery is monitored, and the charging algorithm is adjusted aiming to balance the charge for all the batteries. Through this method, and because each H-Bridge allow the zero voltage level, is easy remove any battery from the circuit, avoiding their collapse. On the other hand, with this topology, when is delivered back to the electrical power grid a small amount of the energy stored in the batteries (V2G), the batteries protection is also obtained through the appropriate control of the H-Bridges, avoiding undervoltages to each battery. As in the charging, during the discharging process,

each battery is monitored, and the control algorithm, which synthesizes the output voltage, is adjusted to insert or remove any battery from the circuit in specific periods of time. In this way, the contribution of each battery is controlled in order to avoid the unbalance between batteries. Also to remove any battery from the circuit, avoiding their collapse, due to undervoltage, the respective H-Bridge is controlled to the zero voltage level.

The main function of the batteries is deliver energy to the electric motor of the EV or PHEV. In this process, due to the control algorithm of the motor, which is adjusted in function of the road and the driver profile, the batteries are subject to different discharging profiles. Consequently, is extremely important protect the batteries and know the batteries SoC. With the presented topology, during this process, the batteries are also protected against undervoltages (insert or remove batteries from the circuit), and the voltage synthesized, which is applied to the motor, is obtained avoiding the unbalance between batteries.

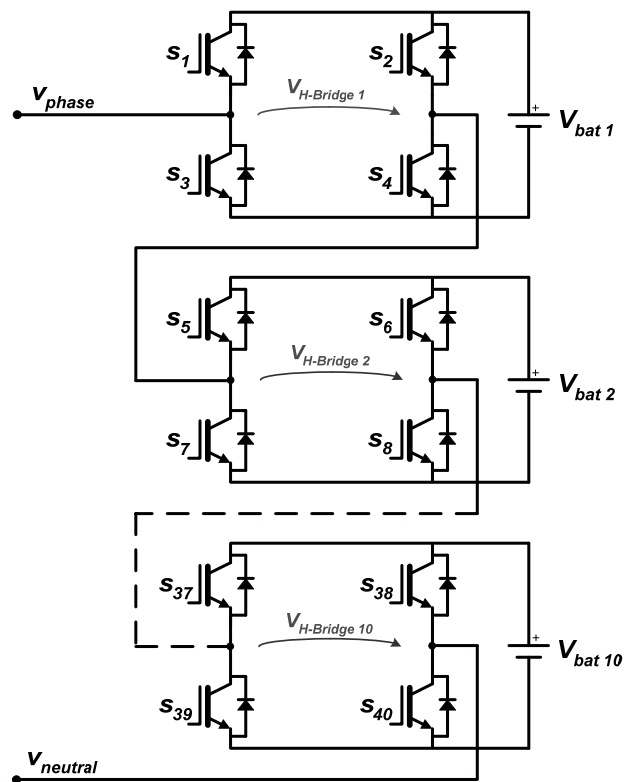


Figure 1. H-Bridge Cascade Multilevel Converter under study, composed by 10 H-Bridges to produce 21 output voltage levels.

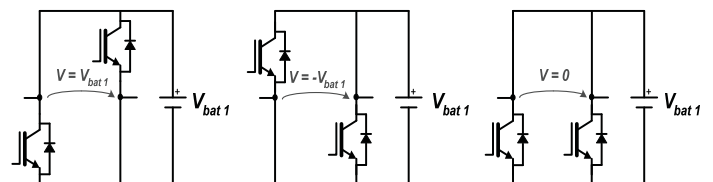


Figure 2. Three output voltage levels of each H-Bridge: $V = V_{bat} V$; $V = -V_{bat} V$; and $V = 0 V$.

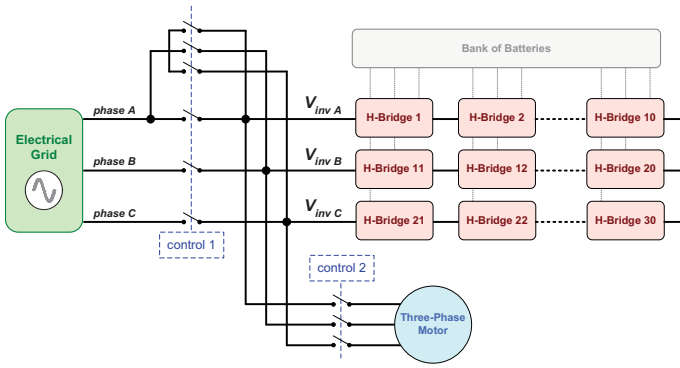


Figure 3. Schematic of a three-phase multilevel converter as interface between the electrical power grid, the batteries, and the electric motor.

Nevertheless, the single-phase multilevel converter presented in Fig. 1 can be combined with other two in order to design a three-phase converter. A three-phase H-Bridge Cascade Multilevel Converter topology has others advantages for applications in EVs and PHEVs. In Fig. 3 is shown the schematic of a three-phase multilevel converter as interface between the electrical power grid, the batteries, and the electric motor. When the vehicle is parked, the converter operates to charge the batteries (G2V) from the electrical power grid. However, as the converter is a three-phase topology and the outlet where the vehicle is plugged can be single-phase, internally, through the *control 1* and *control 2* switch, the three-phases of the converter should be connected in shunt in order to allow the single-phase charging process.

IV. CONTROL ALGORITHM

To the H-Bridge Cascade Multilevel Converter topology presented before, in this section are described the control algorithms (multilevel modulation) of the charging process, the discharging process to the electrical power grid, and to the motor control. In the H-Bridge Cascade Multilevel Converter, the multilevel modulation allows synthetize an output voltage with the required waveform and with adjustable amplitude [3][15][16]. The relation between the number of output voltages levels (n) and the number of H-Bridges (H) is given by the equation (1):

$$n = 2H + 1 \quad (1)$$

Increasing the number of levels, the output voltage harmonics are more reduced and consequently the current harmonics are also more reduced. There are several switching techniques to control multilevel converters, however, to the presented topology, the most common Pulse Width Modulation (PWM) switching techniques are the Phase-Shifted method and the Carrier-Disposition method. In both switching techniques, the control of the semiconductors is based on the comparison of the modulator and the carriers waveforms. Typically, for the application presented in this paper, the waveform of the modulator is sinusoidal, and the waveform of the carrier is triangular. The relation between the output voltage levels (n) and the number of the carriers ($n_{carriers}$) is obtained through the equation (2):

$$n_{carriers} = \frac{(n-1)}{2} \quad (2)$$

To compare and evaluate these two PWM switching techniques are useful the equations (3) (4) and (5) that defines the frequency modulation index (m_f), and the amplitude modulation index (m_a) of the amplitude modulation for the Phase-Shifted method, and of the amplitude modulation for the Carrier-Disposition method, respectively.

$$m_f = \frac{f_c}{f_o} \quad (3)$$

$$m_a = \frac{a_o}{a_{cpp}} \quad (4)$$

$$m_a = \frac{a_o}{n_{carriers} \cdot a_{cpp}} \quad (5)$$

Where f_c is the frequency of the carrier signal, f_o is the frequency of the modulator, a_o is the amplitude of the modulator and a_{cpp} is the peak-to-peak value of the carrier waveform.

A. Phase-Shifted

In this switching technique control are used several carrier signals with the same amplitude and frequency, but with a shift angle between the signals. The relation between the shift angle (φ) and the number of voltage levels (n) is given by the equation (6):

$$\varphi = \frac{360^\circ}{n-1} \quad (6)$$

In Fig. 4 (a) is shown the waveform of the modulators (sinusoidal) and the carriers signals (10 carriers), and in Fig. 4 (b) the output waveform obtained with a THD% = 0.79%. In this case was used $m_f = 4$, and $m_a = 0.48$.

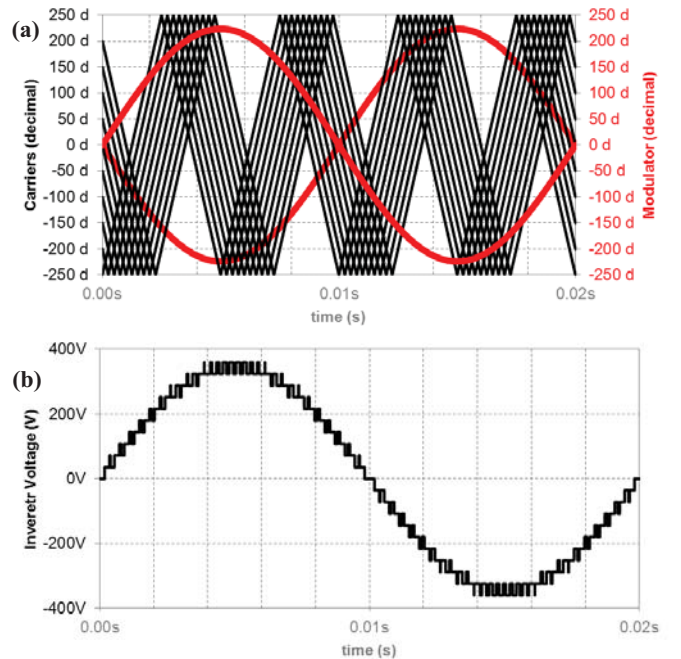


Figure 4. PWM Phase-Shifted ($n = 21$, $m_f = 4$, $m_a = 0.48$): (a) Waveform of the modulators and the carriers; (b) Output of the synthesized voltage.

B. Carrier-Disposition

As in the Phase-Shifted, in this PWM switching technique are used several carrier signals with the same amplitude and frequency. However, instead of the shift angle between the carriers, they are disposed with an offset. In this technique, the carriers and the modulators can be in phase, in phase opposition, and phase opposition alternated. As presented in [3] the better results are obtained when the modulator and the carriers are in phase. The relation between the amplitude of each carrier (a_c) is dependent of the amplitude modulation index (m_a) and the number of levels (n), and is defined by the equation (7):

$$a_c = 2 \frac{a_o}{n \cdot m_a} \tag{7}$$

In Fig. 5 (a) is shown the waveform of the modulators (sinusoidal) and the carriers (10 carriers), and in Fig. 5 (b) the output waveform obtained with a THD% = 0.79%. In this case was used $m_f = 40$, and $m_a = 0.48$.

V. OBTAINED SIMULATIONS RESULTS

In this section are shown the computer simulations results obtained with the operation of the H-Bridge Multilevel Converter topology, considering unipolar PWM Carrier-Disposition as switching modulation, with the modulators and the carriers in phase. The computer simulation model is shown in Fig. 6. These results were obtained with a frequency modulation index $m_f = 400$.

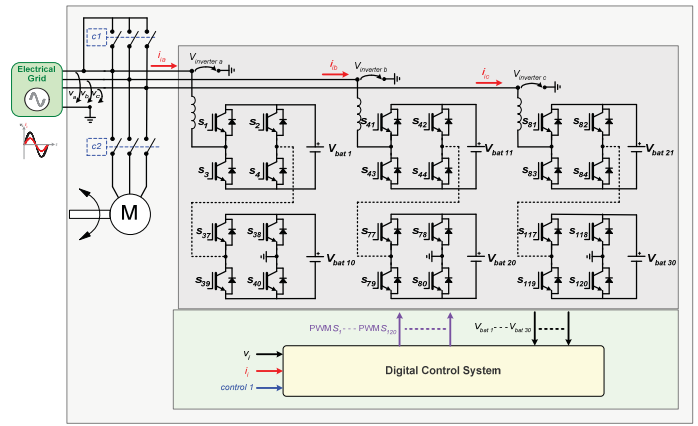


Figure 6. Computer simulation model: H-Bridge Multilevel Converter; Batteries; Electric Motor; and Digital Control System.

In Fig. 7 is shown the voltage waveform of the multilevel converter (THD% = 0.53%), and the consumed current obtained during the batteries charging process (Grid-to-Vehicle - G2V). As shown, during this process the waveform of the consumed current is sinusoidal with unitary power factor, contributing to mitigate the power quality degradation. On the other hand, in Fig. 8 is shown the voltage waveform of the multilevel converter (THD% = 0.53%), and the current when is delivered back to the electrical power grid a small amount of the energy stored in the batteries (Vehicle-to-Grid - V2G). As shown, the current is sinusoidal (in phase opposition with the electrical power grid voltage) with unitary power factor.

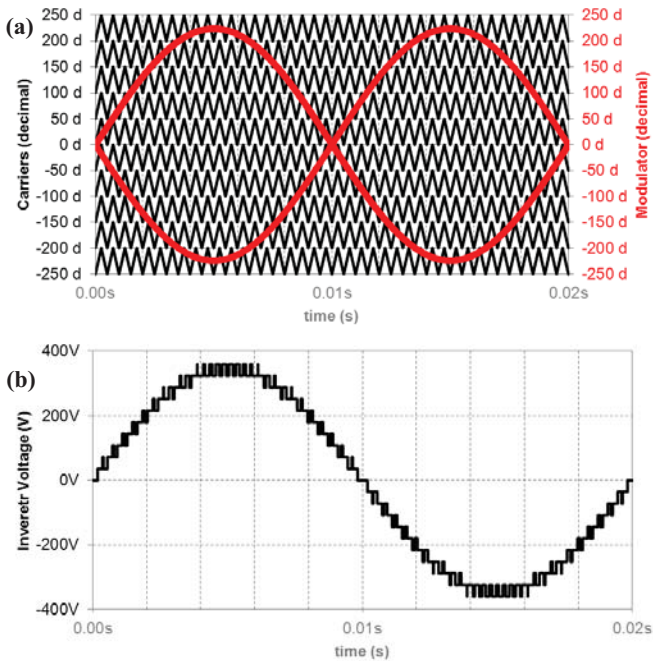


Figure 5. PWM Carrier-Disposition ($n = 21$, $m_f = 40$, $m_a = 0.48$):
 (a) Waveform of the modulators and the carriers;
 (b) Output of the synthesized voltage.

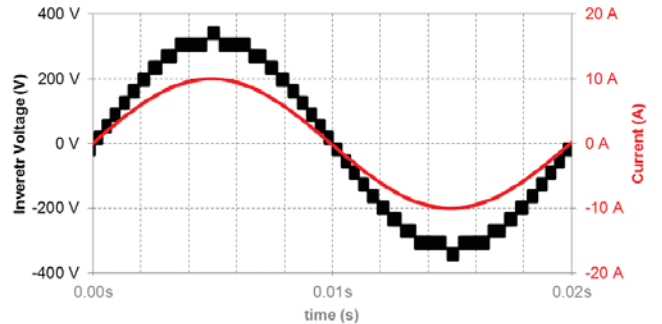


Figure 7. Results obtained during the batteries charging process (G2V): Output voltage waveform of the multilevel converter and consumed current.

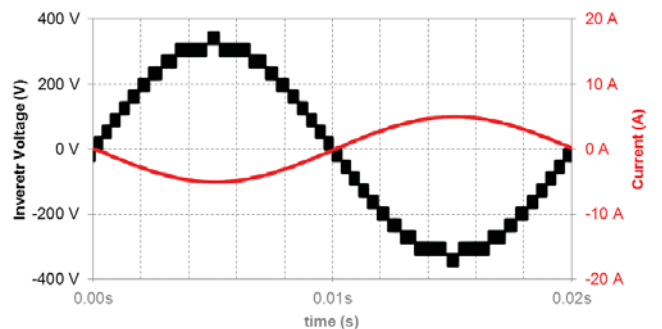


Figure 8. Results obtained during the batteries discharging process (V2G): Output voltage waveform of the multilevel converter and current delivered to the electrical power grid.

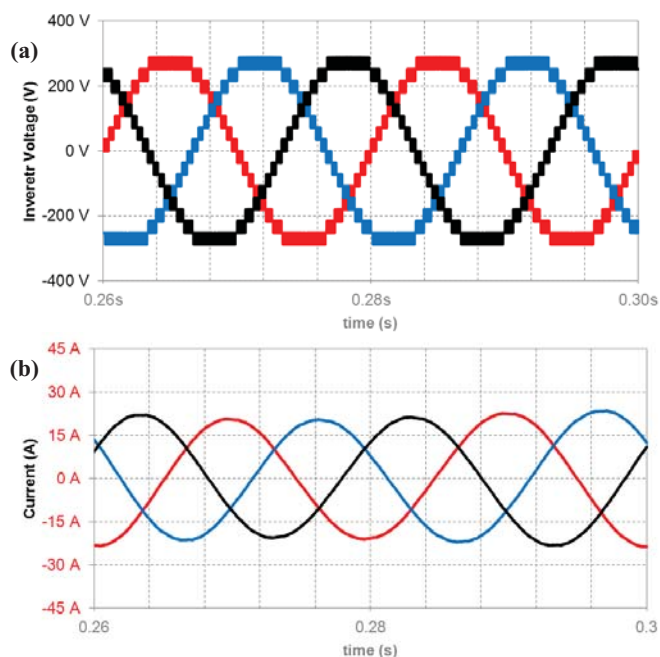


Figure 9. Results obtained during the control of the electric motor: (a) Output voltages waveform of the multilevel converter; (b) Consumed currents.

In Fig. 9 is shown the output voltage waveform of the multilevel converter (THD% = 1.03%) applied to a three-phase electric motor and the consumed current by the electric motor (THD% = 0.83%). The control of the electric motor is not discussed in this paper.

VI. CONCLUSION

In this paper was presented an H-Bridge Multilevel Converter topology for Electric Vehicles and Plug-in Hybrid Electric Vehicles, in order to allow the interface between the batteries, the electric motor of the vehicle, and the electrical power grid. The presented topology is composed by 10 H-Bridges aiming synthetize 21 output voltage levels with a low Total Harmonic Distortion (THD). To control this multilevel converter were presented two switching techniques: Carrier-Disposition and Phase-Shifted.

The interface between the multilevel converter and the electrical power grid allows bidirectional operation, which in one direction consists in charging the batteries from the electrical power grid, in the operation mode denominated as Grid-to-Vehicle (G2V), and in the other direction comprises in delivering back to the electrical power grid a small amount of the stored energy in the batteries (according to the needs of the electrical grid and with the approval of the Electric Vehicle driver), in the operation mode designated as Vehicle-to-Grid (V2G). Aiming to preserve the power quality of the electrical power grid, in both modes of operation the waveform of the AC current of the electrical grid is maintained sinusoidal with unitary power factor. In this paper, these two modes of operation (G2V and V2G) are presented through computer simulations results.

Regarding the application of the H-Bridge Multilevel Converter topology in Electric Vehicles or Plug-in Hybrid

Electric Vehicles, in this paper are also presented computer simulations of the three-phase voltages and currents, synthetized by the multilevel converter, and applied to an electric motor, that can be used in these types of vehicles.

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