Development of a Bidirectional Charger for Electrified Vehicles - Distributed Microgeneration

Ariston Aarão
Bernardo Pelliciari
Eugênio Coelho
Frederico Weissinger
Luis Godoi
Vincent Bigliardi
AVL South America Ltda, Powertrain engineering
Wagner Orlof
AVL Regensburg GmbH, Powertrain engineering

Abstract

The electric vehicle (EV) market is currently a transportation segment under fast growth, while the world is moving towards cleaner fuels alternatives looking for greenhouse gases reduction.

At the same time EVs utilization increase, the electric energy demand from the current power grid also grows. Such scenario has brought the idea of using EVs as power sources to the spotlight to avoid additional investments on the current grid system. Storing significant amounts of energy in EVs would be a reliable way and the V2G (Vehicle-to-Grid) technology can be one of the fastest and safest ways to meet the growing energy demand.

This work presents the project of a bidirectional charger (4,4kW) developed by AVL in Brazil, which has been validated and integrated together with an electric vehicle to the power grid. It is possible to coordinate the energy flux direction between the moment that the vehicle will charge its battery through G2V (Grid-to-Vehicle) and deliver a support current to the grid (V2G). This inserts the EVs on the distributed microgeneration, since the vehicle connected to the grid can supply energy during critical demand peaks or energy shortage in the region, as well as an auxiliary grid stability support.

The bidirectional charging may benefit both EV users, thru tax benefits for instance, as well as the electric power industry which could find an improved load profile along the day.

1. Introduction

Several countries have already set out plans to renew the transport system through increased use of electric vehicles. The European Union, for example, has targets for the complete exchange of conventional fuel vehicles by 2050 [1]. This would dramatically reduce dependence on imported oil and carbon emissions in transportation.

By contrast, the world's energy and electric matrices are significantly non-renewable. In 2019, the world's energy matrix was composed of only 14% renewable energy and the electricity matrix was 27% renewable energy [2]. The popularization of electric vehicles in the market, in fact, would modify the world's electric matrix due to the need to charge the batteries. However, a relevant aspect for the equation would be to identify whether the proportion of the global energy matrix for renewable energies would also reduce.

Despite the low impact to the environment, some of the generation methods can insert side effects into the current generation and distribution system. Consider solar power, for example, which is relatively dependent on other sources of generation, or storage, for certain periods of the day or year.

As a result, for recharging electrified vehicles at night, the generation system should be improved with more generation devices, or storage, to meet the energy demand. EVs can be a solution to this power supply problem in similar situations without the distribution system significantly changing.

Distributed microgeneration applied to electrified vehicles consists of using the energy stored in the batteries of those vehicles and transmitting it partially to the distribution network. For this to be possible, the chargers must be bidirectional to enable both G2V and V2G mode.

2. Impact of PEVs on Distributed Generation

Distributed generation (DG) means generation plants connected to the distribution systems, according to Ackermann [3]. Initially, PEVs were connected to grid for the purpose of battery charging only. However, new smart grid technologies are giving the flexibility of energy discharge to grid and are technically named as vehicle-to-grid (V2G) mode. In this sense, grid connected PEVs virtually act as energy storage devices, i.e. generation plants.

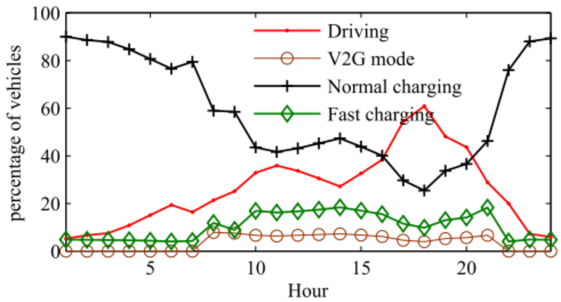

Figure 1. Demand curve proposed by REDDY [4] on his analysis.

According to REDDY [4], the PEVs in V2G mode will help to restore the downstream load point during system failures. This will happen in scheduled and unscheduled V2G modes. Considering the demand curve proposed by REDDY [4], and presented on figure 1, the system average interruption frequency index (SAIFI) would not change while expected energy not served (EENS) and system average interruption duration index (SAIDI) would be improved with higher penetration levels of PEVs and DG.

3. System Overview

The bidirectional charger developed in this material has the premise of being a demonstrator that allows the flow of energy in the directions of charging the vehicle batteries and supplying power from the vehicle to the network. To manage such power flow, some interfaces have been developed that allow the configuration of the load, load depth and discharge allowed when connected to the charger and other parameters necessary to perform the primary functions safely. The main blocks and functions will be described briefly in this paper. Figure 2 represents the overall topology of the developed system.

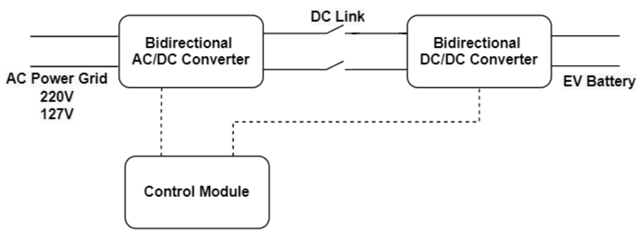

Figure 2. Block diagram of the charger developed.

The system for charger operation is composed of the bidirectional AC/DC converter, two-way DC/DC converter and a converter control module.

3.1. Bidirectional Charger

Bidirectional chargers are intended to allow the current flow not only in the direction of charging the batteries, but also towards the grid, ensuring the supply of energy stored in the batteries to the network. Such flow directions are called grid-to-vehicle (G2V), where the grid supplies power to the battery, and vehicle-to-grid (V2G), where the battery injects power into the grid.

To enable the control of the power flow direction, the converters change the driving mode of power transistors. In addition, a set of keys are used to trigger according to the desired mode of operation. To enable the use of low voltage outlets in the NBR-14136, 2P+T 20A standard, the charger power is controlled according to the network voltage.

The following image shows the assembling of charger control panel. The printed circuit boards are bidirectional DC/DC converter, bidirectional PFC converter and the operating interface.

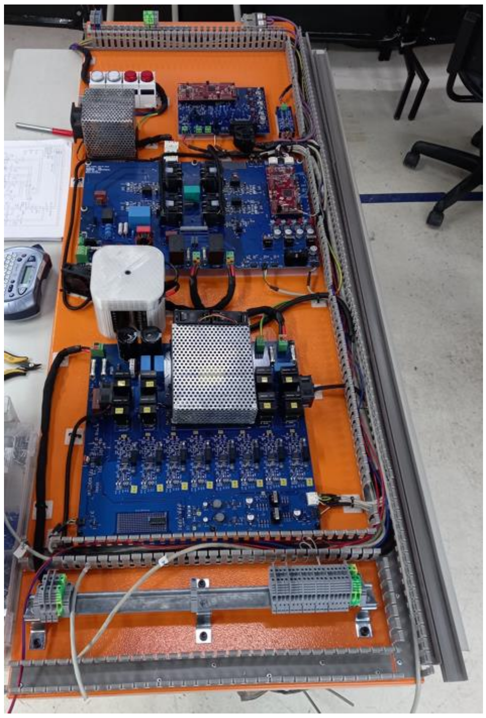
Figure 3. Charger control panel assembling.

The bidirectional charger topology was based on the D1 topology of Annex DD of IEC 61851-23:2014 (Electric vehicle conductive charging system – Part 23: DC electric vehicle charging station).

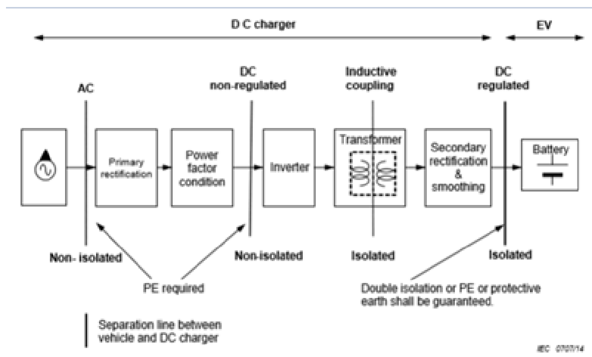

Figure 4. Example of typical isolated system.

This topology has been implemented with the necessary modifications to allow bidirectional flow of energy depending on the control mode of the power transistors.

3.1.1. DC/DC Bidirectional Converter

The bidirectional DC/DC converter is intended to convert the DC link voltage to battery voltage in charger mode and convert the battery voltage to the DC bus into inverter mode. To do that, an insulating transformer was designed that had a transformation ratio that would make the voltage range of the charger's DC bus compatible with the vehicle battery voltage operating range, in addition to providing electrical insulation between the charger and the vehicle.

The converter works on one side as a frequency inverter controlling the transistors in pairs diagonally of the complete bridge so that energy is transferred to the other side of the insulating transformer. On the other hand, transistors work as full wave rectifiers using body diodes.

To improve the rectifier efficiency, the DAB (dual active bridge) control was adopted, where each transistor is controlled in parallel with its body diode, at the correct time, reducing the voltage drop, reducing the dissipated power in each transistor.

To reverse the flow of energy, simply reverse the control of the transistors from one side to the other. The complete system consists of 4 transistors and 4 diodes on each side of the converter. To minimize the size and mass of the insulation transformer, it was necessary to drive the transistors at high frequency (200kHz). To obtain a sine waveform on the current of the transformer windings, it was designed a resonant circuit type CLLLC, composed of the inducers and capacitors of the primary and secondary resonance of the transformer.

It was also necessary to design the insulator transformer to keep a constant magnetization inductance regardless of the transformer operating temperature. Some specifications are shown in the table below.

Table 1. DC/DC Converter Specifications

Spec.	Comment	Min.	Max.
DC Link Voltage (G2V) power grid Voltages	127Vac (G2V)	360V	420V
	220Vac (G2V)	360V	420V
	127Vac (V2G)	340V	380V
	220Vac (V2G)	320V	380V
Battery Voltage Range	127Vac (G2V)	340V	400V
	220Vac (G2V)	340V	400V
	127Vac	340V	400V
	220vac	360V	400V

Table 2. Specifications of the DC/DC Converter.

Spec.	Comment	127Vac	220Vac
Nominal Power	G2V	2438W	4224W
	V2G	2755W	4772W
Battery Nominal Current	G2V	6.1A at 400V	10.6A at 400V
		7.2A at 340V	12.4A at 340V
	V2G	6.9A at 400V	11.9 A at 400V
		8.1A at 340V	13.3A at 360V

3.1.2. AC/DC Bidirectional Converter (PFC).

The AC/DC converter has the goal to convert from direct current (DC) to alternating current (AC) in inverter mode (V2G) and to convert the AC grid voltage to DC and boost voltage in charger mode (G2V).

The conversion from DC to AC is performed by controlling the transistor bridge so that the current flows toward the network. In this way, it is necessary to adjust the frequency and phase of the voltage so that they are synchronized with the frequency and phase of the power grid. In addition, you can control the electrical power returned to the grid during the process.

In the conversion from AC to DC the power transistors are triggered so that the current flows toward the battery. To do that, it is necessary to control the power factor by adjusting the AC current and AC voltage phases. To boost the voltage, the power transistors are switched in high frequency to charge and discharge the series inductor of PFC circuit.

Some AC/DC converter specifications are shown in the tables 3 and 4.

Table 3. AC/DC Converter Specifications

Spec.	Comment	Min.	Max.
DC Link Voltage (G2V) power grid Voltages	127Vac (G2V)	360V	420V
	220Vac (G2V)	360V	420V
	127Vac (V2G)	340V	380V
	220Vac (V2G)	320V	380V

Table 4. More Specifications of the AC/DC Converter.

Spec.	Comment	127Vac	220Vac
Nominal Power	G2V	2540W	4400W
	V2G	2540W	4400W
AC Nominal Current	G2V	20A	20A
	V2G	20A	20A
DC Link Nominal Current	G2V	6A at 420V	10.4A at 420V
		7A at 360V	12.1A at 360V
	V2G	7A at 380V	12.2A at 380V
		8.4A at 320V	13.6A at 340V

3.1.2.1. SiC Mosfets

SiC transistors along with GaN transistors belong to a class of semiconductors called Wide Bandgap semiconductors. These components have been developed for more than 30 years by the semiconductor manufacturers, and their main benefits, compared to pure silicon technologies, are high switching frequency, reduced conduction losses, higher gate to source voltage (which can be above 4V), compatibility with +18V/-4V gate drivers, existence of an intrinsic diode, eliminating the need for external diodes [5]. For these reasons SiC transistors were chosen for the AC/DC converter application and they are another relevant new concept used in this project.

3.1.3. Control Module

The control module executed the logic to control the transistors of the two converters. To do this, it measures signals from the charger sensors and communicates with other charger modules through communication bus. Both converters have two control modes: one for charger mode (G2V) and one for inverter mode (V2G).

3.1.3.1. DC/DC Converter Control Loops

For both inverter and charger mode, open loop control was adopted for this converter. Then, two PWM controllers were adopted to trigger the electronic switches, since no synchronous driving was used between the converter switches. Thus, duty cycle is maintained at 50% and frequency at 200kHz. Dual Active Bridge (DAB) control was used to control the rectifier to improve conversion efficiency.

3.1.3.2. AC/DC Converter Control Loops

For charger mode, the inverter has two control loops. The internal loop makes the current control, by having a faster dynamic, through a PI controller and aims to make the correction of the power factor. The output of this controller directly activates the PWM controller to generate the pulses on the electronic switch gates.

The outer loop does both voltage and current control. To do that, two PI controllers were used. For charger mode, it is necessary to carry out both control modes so that it is possible to charge in constant current and constant voltage modes.

For the inverter mode, a resonant proportional control loop was used, which is commonly used in inverters connected to the network. The purpose of this controller is to manage the current intensity that will be returned to the network.

The synchronism with the network is accomplished through an enhanced phase-locked loop (ePLL) module, which consists of a phase follower with feedback loop.

4. Under Development, Next Steps & Improvements

4.1. SOFC Integration

Unlike the Polymer Electrolyte Membrane Fuel Cell (PEMFC), which is widely use in different commercial applications, the Solid Oxide Fuel Cell (SOFC), which represents the new generation of technology aimed at fuel cells, operates at higher temperatures, such as 800°C, and have cells composed of a solid ceramic membrane between the electrodes.

SOFC generators have high performance with low pollution rate. The system efficiency is estimated to be between 50% and 60%. However, these values could reach up to 85% if the thermal energy generated by the system is recovered and reused. Another advantage of this new technology would be the possibility of using renewable energies as fuel for the system, such as ethanol, which is very common in Brazil.

In a simple way, the operation of SOFC consists of a reformed mixture with high temperatures between ethanol and water that enters the anode of the Stack and undergoes reduction, while the cathode receives oxygen that undergoes oxidation and crosses the ceramic membrane. Figure 5 demonstrates the SOFC generation process [6].

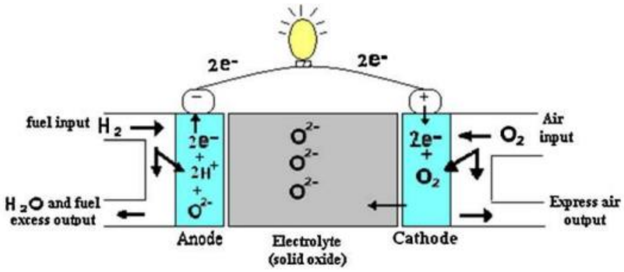

Figure 5. SOFC internal description.

On the other hand, the high temperatures of the SOFC generator also have some disadvantages, such as slow start-up and reduced durability of the system. Thus, this generator is not used in mobile systems, such as in the automotive area [7]. However, SOFC is already present in stationary generation systems, therefore, there is a possibility of its integration with the bidirectional charger.

As represented in figure 6, the SOFC can be inserted into the charger system through a DC-DC converter allowing the generated energy to be used both to charge the vehicle and to return to the grid.

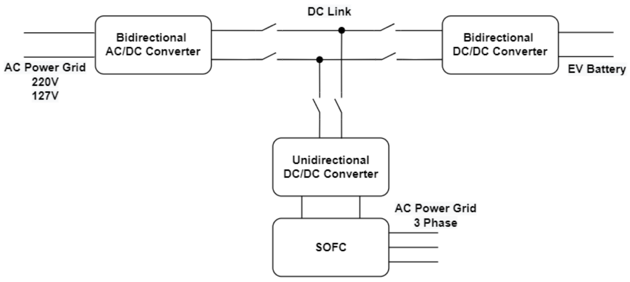

Figure 6. Block diagram of the charger including SOFC system integration.

4.2. Energy Management App

For battery discharge level management, an application that allows the user/driver to configure the power transfer parameters has been developed. All current, voltage and SOC data acquisition is shared in the cloud through an IOT platform. Then, it is possible to manage the amount of energy transmitted between vehicle and power grid in both G2V and V2G modes.

4.3. Embedded Charger

The use of the charger as a demonstrator was validated through the panel shown in Figure 3. However, it would also be possible to integrate the charger embedded to the vehicle. This would require reducing the size of PCBs and heat sinks, using the vehicle's cooling system to cool the charger components, for example. In addition, a fully thought-out mechanical design for the vehicle embedded charger must also be considered.

Integrating the charger into the vehicle would benefit the driver by making it possible to charge at any residential outlet.

5. Conclusion

Vehicle bidirectional charger is a device capable of recharging the vehicle battery and transmitting the energy stored in the batteries to the grid. These chargers will most likely have a great impact on the world energy distribution system, since through this equipment the vehicle becomes a relevant component for distributed microgeneration. This project validated the concept of bidirectional chargers through the developed demonstrator.

Electric vehicles connected to bidirectional chargers impact the distribution system through the ability to assist the system in situations of network faults or at peak demand times from certain considered scenarios.

The implementation of this demonstrator brings several improvements in the system. First, using the embedded charger into the vehicle can make it easier for cars to be charged, reducing dependence on charging stations for electric vehicles. Furthermore, the development of IOT applications to manage battery charging and energy transmission back to the distribution grid is also a relevant factor for the feasibility of this concept.

Bidirectional chargers, combined with a clean and CO2 neutral technical solution as Ethanol SOFC, is a new path to produce clean energy to Electrical Vehicles or to the grid on demand.

6. Acronyms

Acronyms	Meaning
EV	Electrified Vehicle
PEV	Plug-in Electric Vehicle
G2V	Grid to Vehicle
V2G	Vehicle to Grid
DG	Distributed Generation
SAIFI	System average interruption frequency index
EENS	Expected energy not served
SAIDI	System average interruption duration index
AC	Alternate Current
DC	Direct Current
DAB	Dual Active Bridge
PWM	Pulse Width Modulation
PI	Proportional Integral
ePLL	Enhanced Phase Lock Loop
PCB	Printed Circuit Board
IOT	Internet of Things

7. References

[1] Morris, B. Foiadelli, F. Longo, M. Zaninelli, D. *"A study of the Integration of Distributed Generation and EVs in Smart Cities"*. IEEE, 2017.

[2] EPE. *"Matriz Energética e Elétrica"*. Available at <https://www.epe.gov.br/pt/abcdenergia/matriz-energetica-e-eletrica >. Accessed on May 15 of 2022.

[3] Ackermann, T. Andersson, G. Söder, L. *"Distributed Generation: a definition"*. Elsevier, April 2001.

[4] Reddy, G. Goswami, A. Choudhury, N. *"Impact of plug-in electric vehicles and distributed generation on reliability of distribution systems"*. Elsevier, February 2018.

[5] Infineon. *"CoolSiC Technology Details"*. Available at <https://www.infineon.com/cms/en/product/technology/silicon-carbide-sic/technology-details/>. Accessed on May 15 of 2022.

[6] Mekhilef, S. Saidur, R. Safari, A. *"Comparative Study of Different Fuel Cell Technologies"*. Elsevier, 2011.

[7] Guangul, F. Chala, G. *"Comparative Study between the Seven Types of Fuel Cells"*. Applied Science and Engineering Progress, 2020.