Vehicle to Grid (V2G) operation for an On-Board charger (OBC)

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Abstract— **The intent of this thesis is the description of the development process of a power converter able, beside charging the battery of an EV, of injecting back energy from the battery to the grid network, opening the doors for Vehicle-to-Grid AC (*V2G-AC*) technology. The preliminary studies, at the time in which this thesis has been written, shows a lack of proper standards specifically made for the use on-board chargers mounted on passenger vehicles for V2G applications. IEEE 1547 standard define the guidelines for generic applications regarding grid-connected devices and for this reason, most likely future standards regarding V2G in specific will be based on this one. Before the realization of an hardware prototype a simulation has been developed, considering a 3-phase 2-level inverter as power converter. The control strategy use to compute switching patter, has been implemented in the (d,q) rotating frame that allows for an easier computation of the references by means of Clarke-Park transformations.**

I. Introduction

Since the late 19th century, the automobile and motor-driven vehicles in general, became the main means of transport for people and goods. Nowadays almost everyone own a private car and a projection shows that the estimating total number of vehicle in our society will reach more that two billion in 2030[1]. All comes with a cost: emissions. the main goal of the European Green Deal is targeting for a 90% reduction of pollutant from transportation in comparison to 1990 levels, allowing Europe to become climate-neutral in 2050[1]. The only way to reduce carbon emissions from vehicles is to electrify them.

The amount of battery-powered vehicles is constantly increasing and this facilitates the process of becoming carbon neutral, but this goal will be reached only when the electricity used to power these vehicles is generated from renewable sources. Generally speaking, electric vehicles require 15-20kWh of energy in order to be able to drive 100km and considering that in 2030 the percentage of total battery-powered vehicles on the road will be the 30% [2], this will translate in a total energy request of $1110TWh$. If not well managed, this amount of power request could bring to many problems to the grid operator.

The continuous growth of electric vehicles could also help in supporting the current grid, acting as energy storage. Demand of electricity is constantly increasing and with most of the EVs owned by private people that spends the most of their time just parked, it would be very useful to take advantage of this dead time in support of the grid, achieving a better stability of the grid thanks to V2G technology.

On average, a private electric vehicle is driven for only the 12.1% of the day [2] and removing the necessary time to charge the battery, this lead to an important dead-time of which V2G technology could take advantage of. Compensation of the user that participate to the V2G scenario is very important to keep him interested in providing his participation: the car battery became an energy reserve from which the electrical provider can buy back from the EV owner. The impact of V2G services on the total cost of ownership could bring to important revenues, up to €11.000 in the case of support for imbalance services and using semi-public charging stations [3].

II. Standard Requirements

IEEE Std 1547 is a standard stating the base of requirements of interconnection for Fuel Cell, Photovoltaic, Energy Storage, and more in general all the distributed energy resources (DERs) that exchange power with the grid network. Overall, this standards establish requirements for: interconnection integrity and performance, Reactive Power capability and voltage/power Control,Response to Area EPS abnormal condition, Power quality, Islanding and Interoperability. Depending on the application, the standard gives different requirements depending on the category of the device: Category I, II or III for operation during abnormal conditions and Category A and B for operation during normal conditions. As example, the standard suggests that an inverter sourced by energy storage, should be compliant with abnormal condition requirements of Catergory II.

III. Control Theory

Converters for charging application in automotive field can be differentiated in two categories: Single-phase Converters and Three-phase Converters. Three-phase converters are more suited for higher power since they can transmit three times more power than a single-phase one, in a more energy efficient way. For these reasons, the topology used in this thesis is a 2-level 3-phase inverter. Controlling the current flow in a very precise manner is critical for this application: for this reason a *Current Controller* has been implemented. To reduce the complexity of the system and use less controllers is possible to implement a control scheme in the (d,q) rotating frame, where the voltage and current waveforms that in the abc frame are sinusoidal, are now DC waveform in steady-state conditions, easier to analyze and control. Park transformations allows the voltage conversion from abc to dq.

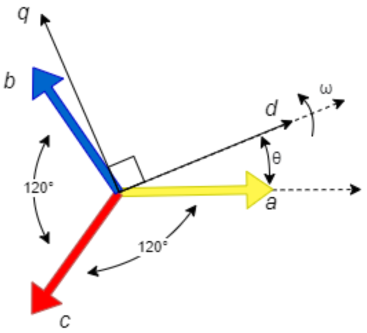


Figure 1: abc frame and dq rotating frame

The current controller must be capable of precisely control the amplitude and the phase shift of the current waveform, generating active power $P(t)$ and reactive power $Q(t)$.

$$\begin{aligned} P_s(t) &= \frac{3}{2}[V_{sd}(t)i_d(t)] \\ Q_s(t) &= \frac{3}{2}[-V_{sd}(t)i_q(t)] \end{aligned} \tag{1}$$

Therefore, in order to control $P_s(s)$ and $Q_s(s)$ it is possible to compute the reference currents to impose to the system. Figure2 shows the complete diagram of the current controller implemented for the current-controlled VSC system wich output is the modulation signal in dq-frame.

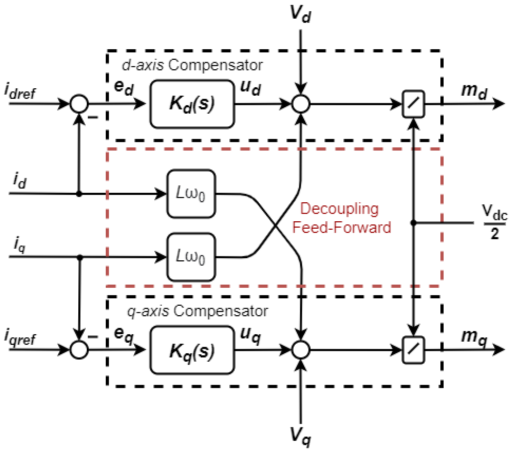
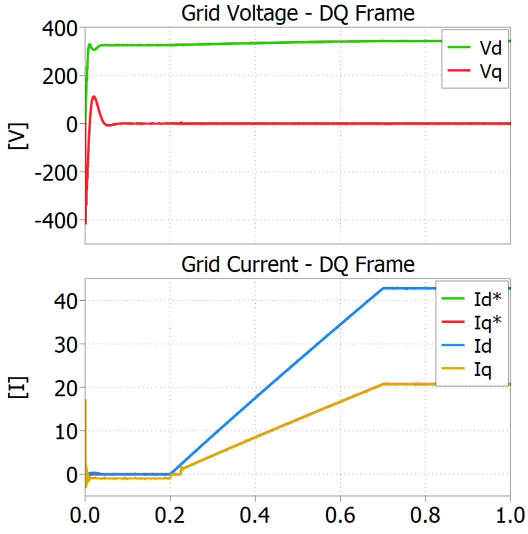


Figure 2: Control block diagram of a current-controlled VSC system.

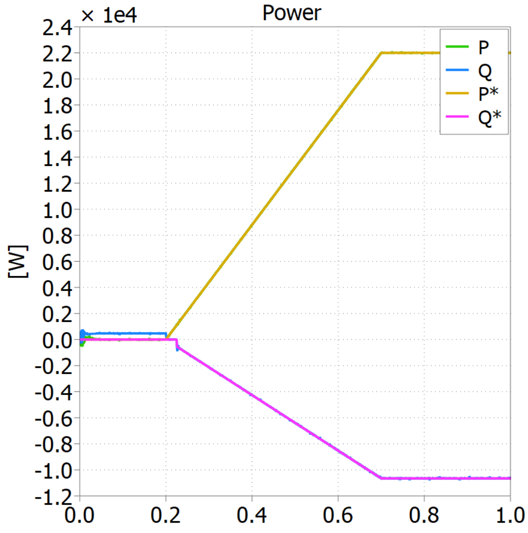
IV. Simulation Results

As expected the system behaves correctly: at start-up the main switch closes, connecting the output of the inverter to the grid, that in this case has been simulated as a perfectly balanced grid, without any harmonic distortion.

In Figure 3a is possible to notice how the PLL is also perfectly latching to the grid, generating a steady DC value of voltage, with a null *q-axis* component. The control start at 0.2s and the requested power is ramped up reaching the steady state value of 22kW in 0.7s. A power factor $PF^* = 0.9$ has been requested for this example.



(a) *Voltage and Current in (d,q) rotating frame*



(b) *Active Power $P(t)$ and Reactive Power $Q(t)$*

Figure 3: Simulation Results

V. Experimental Results

With satisfactory simulation results, the step after has been to realize an actual hardware prototype of the system where to test the control algorithm.

The overall system interconnection is shown in Figure 5 and consists of a digital board capable of processing measurements and compute switching pattern, a power board containing the switches and sensors, LC Filter and the main switch to disconnect the inverter output from the AC source.

With everything connected, the DUT has been tested by slowly increasing both AC and DC voltages until safely reaching the nominal values of $800V_{DC}$ and $230V_{rms}$. Figure 6 shows the results of the test at nominal voltage and for a total power transfer of $15KW$ (Only one of the phases

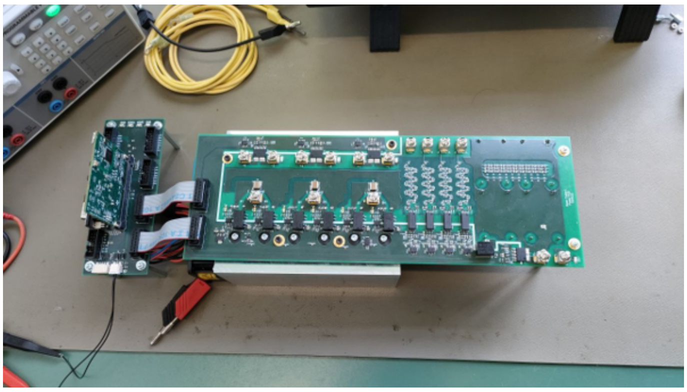


Figure 4: Board Prototype

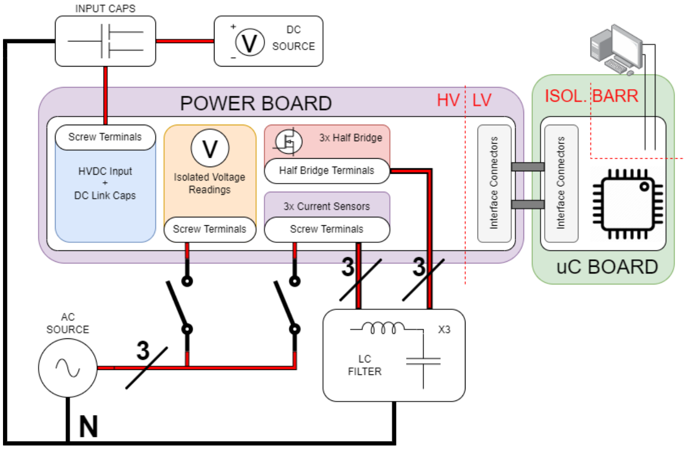


Figure 5: Experimental test-bench diagram.

is shown in the picture). In Figure6 it can be noticed how the current flow is in phase with the grid voltage, thus proving the correct operation of both grid synchronization algorithm and the current control. With the data extracted from measurement it was possible to measure the spectrum and compare it with the standards requirements. Figure 7 shows in blue the maximum allowed value of harmonics distortions content of the grid current from the IEEE 1547 standards, while in orange are the measured one.

Although the results are promising and fulfill the harmonic distortion content limitation of IEEE 1547 Standard, one of the main problem highlighted by spectrum analysis of Figure 7 is the high amplitude of the 3rd harmonic distortion, that results in a non-zero current flow In on the neutral line, as it can also be seen in Figure6. This is explained by the connection of the neutral with both the center point of the star connected AC filter capacitors and the midpoint of the DC-link. This kind of connection is due to the adopted unipolar voltage sensing circuit. To face this problem, could be helpful to investigate more advanced control techniques such as adaptive controls or add another leg to drive the neutral line, realizing a three-phase 4-wire converter.

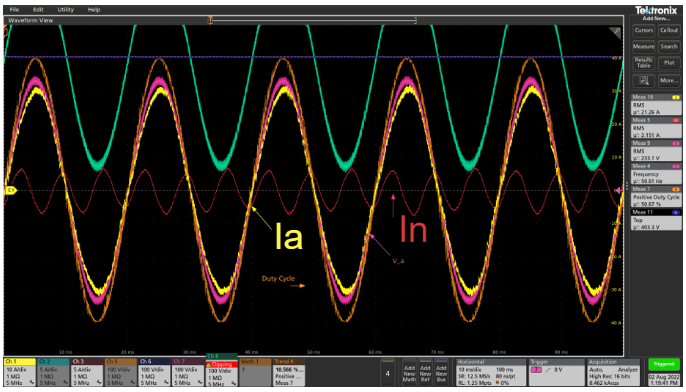


Figure 6: 15KW Power Transfer Test.

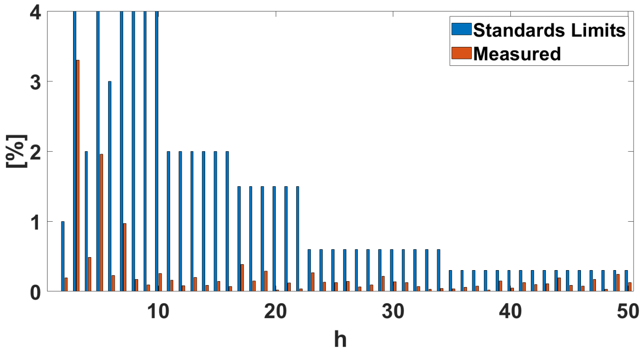


Figure 7: Current Harmonic Content.

VI. Conclusions

With the goal of reaching decarbonization and reduce emission by switching to more renewable energy, it is then essential to manage and support the grid using personal battery-powered vehicles as energy storage. Unfortunately the literature lacks of proper standards specifically made for the use of on-board chargers mounted on passenger vehicles for V2G-AC applications. Simulation on PLECS and test of the prototype shown promising results, achieving active and reactive power control with harmonic emissions within the limits of IEEE 1547.

In conclusion, it is possible to summarize my contribution to this thesis as:

- Familiarizing with OBC concepts;
- Review of existing V2G projects and architectures;
- Research of applicable standards for V2G OBC;
- PLECS Simulation of the power converter;
- Realization of the actual prototype;
- Test of the converter prototype in the lab.

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