Onboard battery charger for electric vehicles

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What is an onboard battery charger?

An onboard battery charger (OBC) is an automotive power electronic converter tailored to charge an EV directly from the grid. As the name suggests, the onboard battery charger is integrated into the vehicle and is carried by the vehicle at all times. Because of this, researchers and Original Equipment Manufacturers (OEMs) are constantly innovating to ensure that OBCs become lighter and more efficient. A lighter onboard battery charger increases the range of the electric vehicle and a more efficient charger decreases the amount of energy wasted from the grid. This reduces the overall cost per mile for an EV driver.

While DC fast charging is an alternative to charging an EV using an OBC (see AN007 – Fast electric vehicle charger with intermediate energy storage for an example), the convenience of charging the vehicle from the much more accessible (including at home) AC grid is not to be underestimated.

Onboard battery charger design example

Design and control objectives

1. An OBC must be able to control the battery charging current/voltage
2. An OBC must be able to maintain unity power factor when charging the battery
3. For safety, an OBC should be isolated from the grid
4. As mentioned in the introduction, it should be small and light

In addition to the 4 core objectives, if the onboard battery charger is able to operate bidirectionally, it opens the door for vehicle-to-grid (V2G) applications as well.

When considering objectives 1 and 2 from the list above, a common solution is to consider two-stage converters, which simplify the decoupling of the two distinct controlled variables, namely the battery charge current, and the power factor from the grid [1].

Similarly, when considering objectives 3 and 4 from the list above, the design of the onboard battery charger is constrained to high-frequency isolation transformers because the weight and volume of a transformer are inversely proportional to its operating frequency. High-frequency transformers are common in isolated DC/DC converters, resulting in most onboard battery chargers having a non-isolated active rectification stage and an isolated DC/DC battery charging stage [1].

Typical topology

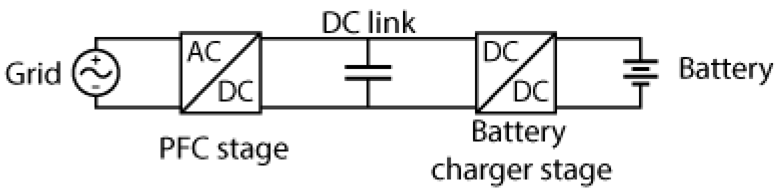

Figure 1: Two-stage converters are a popular implementation for onboard battery chargers

The two-stage approach shown in Figure 1 is a common configuration for onboard battery chargers. Multiple converter topologies can be implemented to achieve the control objectives of each stage, and the choice made depends on multiple factors such as controllability, cost to manufacture, targeted efficiency, etc.

Some examples are listed below:

PFC stage

- Boost PFC converter
- Bridgeless dual-boost PFC converter
- totem-pole PFC converter

Battery charger stage

- LLC converter
- DAB converter
- Full bridge converter

In addition, the choice between implementing a three-phase onboard battery charger (max 22 kW charging) and a single-phase version (max 7.4 kW charging) also affects topology selection. This article focuses on the single-phase implementation of the OBC, as phase shedding [2] in 3-phase OBCs means that single-phase control strategies are also relevant for three-phase converters.

Onboard battery charger control strategy

Power factor correction

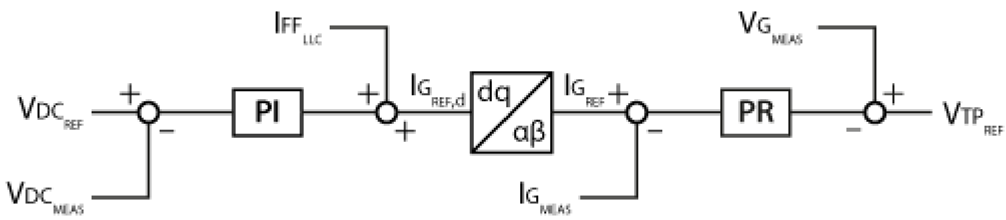

Figure 2: Control loop for PFC

The power factor controller, shown in Figure 2, is a 2-stage cascaded controller based on the control from TN113 – Single-phase totem-pole PFC rectifier. The inner loop controls the grid current using a PR controller, and the outer loop controls the DC bus voltage using a PI controller.

Due to the nature of the single-phase grid connection, a 100 Hz (or twice the grid frequency) power ripple is inevitable, as no power from the grid can be transferred during the instances where the grid voltage is equal to zero. To ensure that the outer loop does not attempt to correct this ripple, its bandwidth must be reduced to below 100 Hz.

Feedforwarding a current equivalent to the charging power from the LLC ensures that the bus voltage does not drop during transients, improving controller performance.

Battery charger control

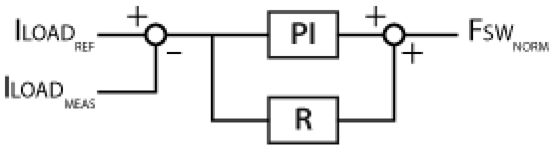

Figure 3: Resonant controller implemented in parallel to the PI controller

Compared to the rating of EV batteries, many onboard battery chargers charge the traction battery at a relatively low C-rate. Because of this, the charge current is limited either from the grid connection or the rating of the OBC itself. The charge current can therefore be set constant to the maximum rated current. At higher state-of-charges, the traditional technique is to charge using constant voltage to ensure that the battery is not overcharged [3].

It is noteworthy that research on batteries is constantly evolving, and the charging technique mentioned above is only one of many possible techniques that can be implemented [3].

Furthermore, due to the long charging duration for EV batteries, the dynamics of the current tracking are less relevant compared to the rejection of the 100Hz ripple on the DC bus. Therefore the control implemented in this section, shown in Figure 3, is an extension of the control implemented in [TN126 – LLC resonant converter for battery charging applications](). Along with the PI controller, a resonant controller is added in parallel to better reject the 100 Hz ripple.

The k_r gain must be tuned conservatively to ensure stability as it is a linear controller acting on a non-linear plant (similar to the PI gains discussed in TN126). This is why the 100 Hz ripple cannot be completely eliminated by this control method.

Since the grid frequency is not constant and can vary slightly depending on grid conditions, the resonant portion of what is effectively a PIR controller should be tuned to tolerate a small deviation in ripple frequency

Realization of an onboard battery charger using imperix products

System setup

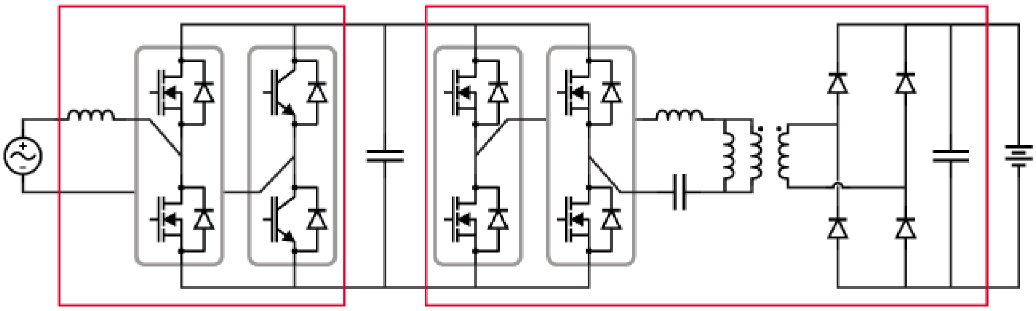

Figure 4: Schematic of onboard battery charger demonstrator

The topology considered for the practical demonstration of the onboard battery charger, shown in Figure 4, is a totem-pole active rectifier in series with an LLC series resonant converter. The only non-standard component utilized in the commissioning of this system is the custom resonant tank for the LLC converter. Additional details about it can be found in TN127 – Tank circuit design for an LLC resonant converter. The system is assembled in a standard 19″ server cabinet and is shown in the figure below.

Standard component list

- 1x B-Box RCP, used as programmable controller
- 1x 2.2mH inductor, found in Passive Filters Box
- 1x AC grid panel 230 V
- 1x reversible DC power supply, used as a battery emulator at the output, with a configurable voltage
- 1x DIN 800 V voltage sensor, to measure the grid voltage
- 1x DIN 50 A current sensor, to measure the the output current

Due to the varying conditions that each module will be operating in, the optimal module for each part of the OBC, shown in Figure 6, is different:

- x1 PEB 8038, used for the high-frequency leg of the totem-pole rectifier
- x1 PEB 4050, used for the low-frequency leg of the totem-pole rectifier
- 2x PEB 8024, used to create a high-frequency SiC H-bridge
- 2x PEB 4050, used without any gate signals as a rectifier for the transformer current

Figure 5: The OBC demonstrator fitting neatly into a cabinet

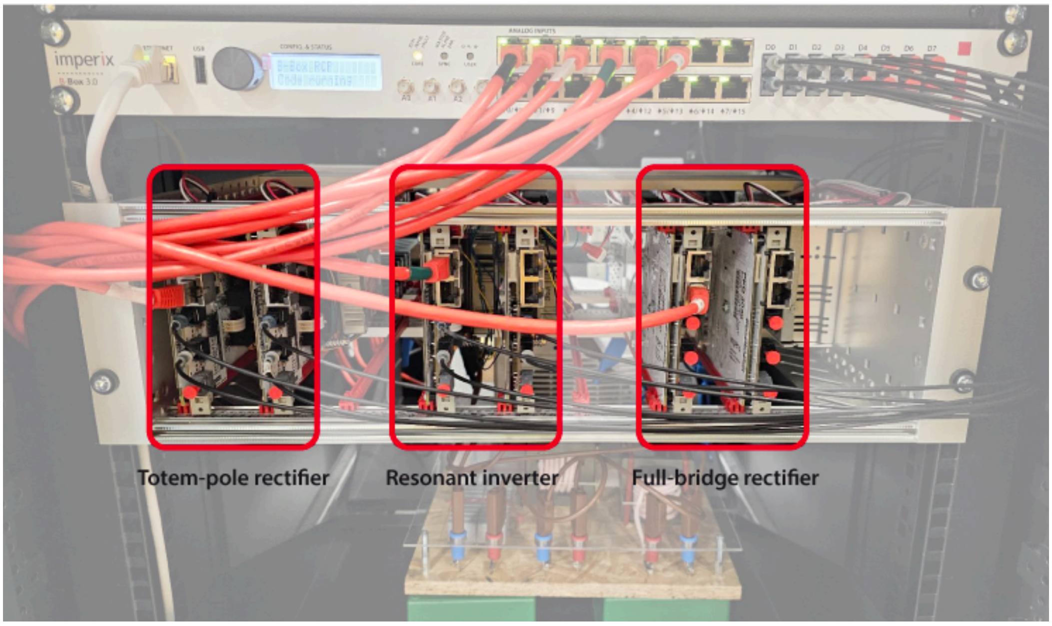

Figure 6: A total of 6 half-bridge modules are required to implement the onboard battery charger: the totem-pole rectifier, the resonant inverter, and the full-bridge rectifier

It is recommended to use an [open rack](#) when mixing modules such that it is easier to double-check, and fix, the wiring if required

Control implementation in Simulink

The control strategy described in section 2.3 can easily be implemented onto the B-Box RCP using Simulink with the [ACG SDK](#). The model shown in the figure below can be downloaded and run both offline and on the physical controller.

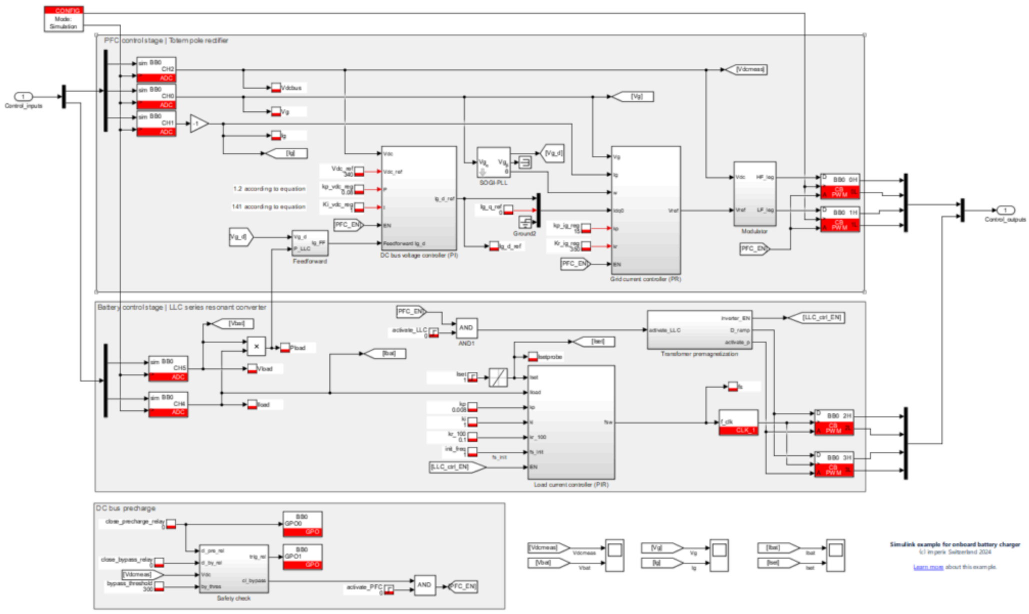

Figure 7: Top-level view of control implemented using Simulink and ACG SDK

[Download **AN010_OBC.zip**](#)

Onboard battery charger experimental results

The results in this section are limited to a specific battery voltage and are obtained by emulating the battery with the reversible DC power supply set to 400 V.

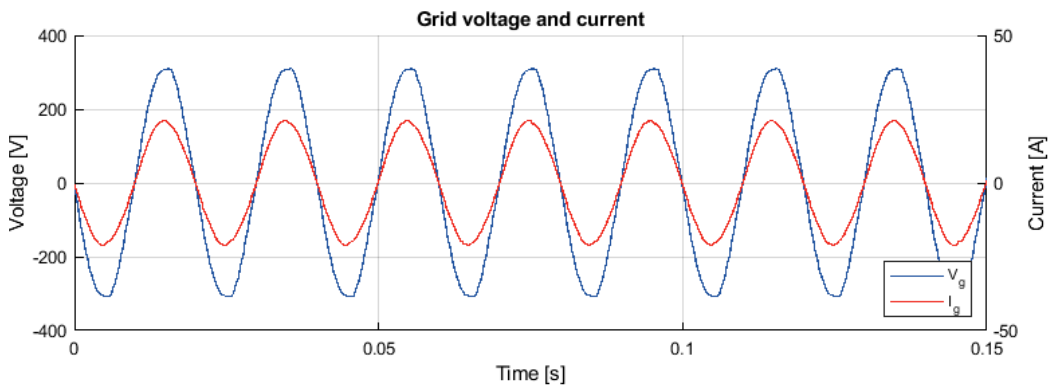

Figure 8: The grid voltage and grid current when the current setpoint is 8.75 A

Figure 8 shows the grid voltage and current. The power factor of the onboard battery charger is 99.94% with 2% THD.

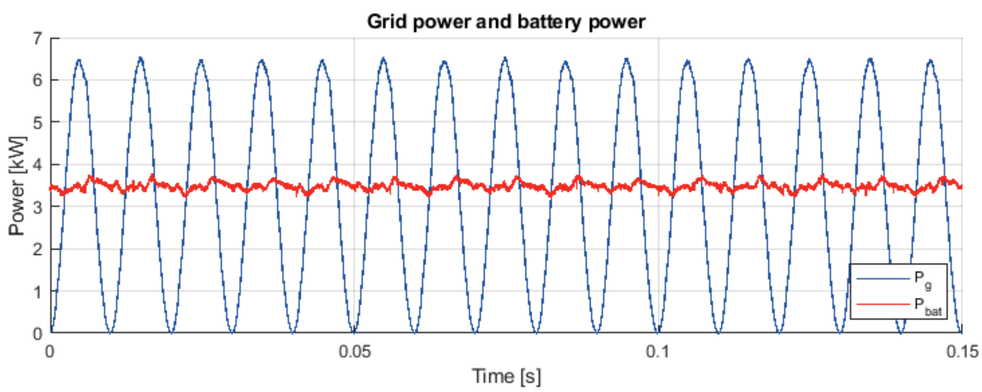

Figure 9: The power from the grid and the battery charge power when the current setpoint is 8.75 A

Power ripple from a single-phase system is inevitable and energy storage is required to mitigate its effects. Figure 9 demonstrates that despite the power ripple due to a single-phase connection to the grid, the energy stored in the DC bus allows for constant current charging of the battery.

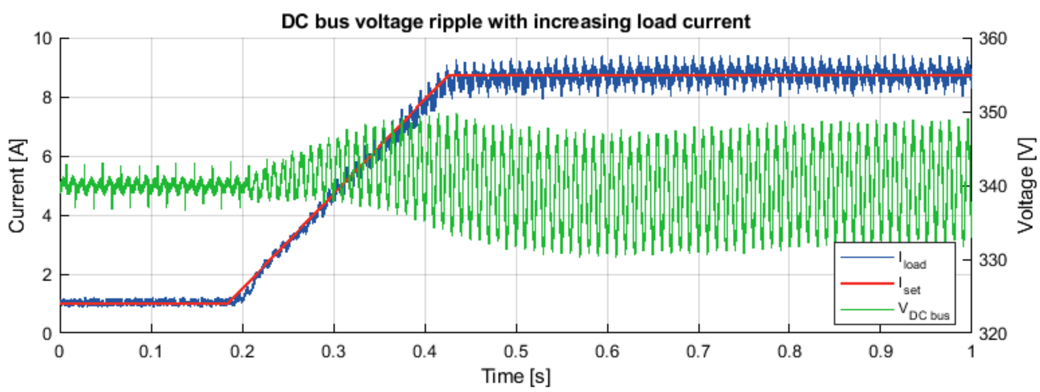

Figure 10: The charge current and the DC bus voltage as the charge current increases from 1 A to 8.75 A

Figure 10 illustrates the 100 Hz DC bus voltage ripple rejection of the LLC converter using the control strategy described in section 2.3.2. While the DC bus voltage ripple increases proportionally to the load current, the non-linear transfer function of the LLC stage results in the ripple rejection varying non-linearly with the load current.

When I_{set} is equal to 8.75 A, the voltage ripple is 17 Vpp, resulting in the voltage gain fluctuating from 1.15 to 1.21, and the current ripple is 1.25 A.

While the results outlined in this article show the operation of the totem-pole rectifier and LLC series resonant converter in a combined system, it is recommended to start by reading and implementing a totem-pole PFC and an LLC converter in isolation, such that each stage of the OBC can be individually validated. This is especially important given the non-linearity of the LLC converter.

References

[1] A. Khaligh and M. D'Antonio, "Global Trends in High-Power On-Board Chargers for Electric Vehicles," in *IEEE Transactions on Vehicular Technology*, April 2019
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[3] W. Shen, T. Tu Vo and A. Kapoor, "Charging algorithms of lithium-ion batteries: An overview," in *Proc. of ICIEA*, Singapore, 2012