Achieving High Efficiency and Enabling Integration in EV Powertrain Subsystems Using C2000™ Real-Time MCUs

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There are a variety of architectures and topologies used in electric vehicle powertrain subsystems like onboard chargers (OBCs) and high-voltage to low-voltage DC/ DC converters. Efficient control and management of the power flow in these systems can be achieved using one or more real-time microcontrollers (MCUs).

At a glance

This paper discusses common control challenges of onboard chargers and high-voltage to low-voltage DC/DC converters, and the benefits of C2000™ real-time MCUs in these subsystems.

1 Totem-pole PFC and CLLLC topology for onboard chargers

A totem-pole bridgeless PFC improves efficiency by lowering the number of power devices in the current path, while enabling bidirectional operation. The CLLLC isolated DC/DC converter provides a soft-switching capability to enable a higher switching frequency and smaller magnetics size.

2 Peak current mode control for high-voltage to low-voltage DC/DC converters

The analog integration on a C2000 real-time microcontroller enables peak current mode with control loops fully in hardware.

3 Scalable portfolio of real-time MCUs for onboard chargers

C2000 real-time MCUs offer a scalable portfolio to address the variety of integration needs and discrete options in on-board charger systems.

The electric vehicle (EV) market has been growing rapidly since 2010, with original equipment manufacturers (OEMs) announcing EV models through 2025. This evolution toward more pure EVs rather than hybrids is a reaction to government environmental policies mandating a transition away from internal combustion engines.

Higher-capacity battery packs, while reducing consumer anxiety related to limited driving ranges, place increasing demands on an EV's power electronics – specifically the onboard charger (OBC), which not only needs to accommodate higher power ratings to accommodate higher power capacities, but must also possess higher power density and higher efficiency to reduce weight of the vehicle and reduce cost per charge.

The emergence of gallium nitride (GaN) and silicon carbide (SiC) wide-bandgap power semiconductors has provided an opportunity to massively shrink the size and weight of the power electronics in EVs given their ability to operate efficiently at much higher switching frequencies than silicon.

The challenge for OEMs and Tier-1s is to provide OBC solutions that can support multiple geographic regions with different power-grid infrastructures. For example, higher power EV chargers in China need to support connections to a three-phase power line, while EVs in the U.S. need to connect to a single-phase power line. OEMs want to supply variants with power ratings ranging from 3.3 kW to 22 kW typically – and as high as 44 kW in some cases.

The most critical systems in an EV powertrain are the OBC that is used to charge the high-voltage battery, the high-voltage to low-voltage DC/DC converter which charges the 12-V/48-V battery, and the traction inverter that controls the EV motor, shown in Figure 1.

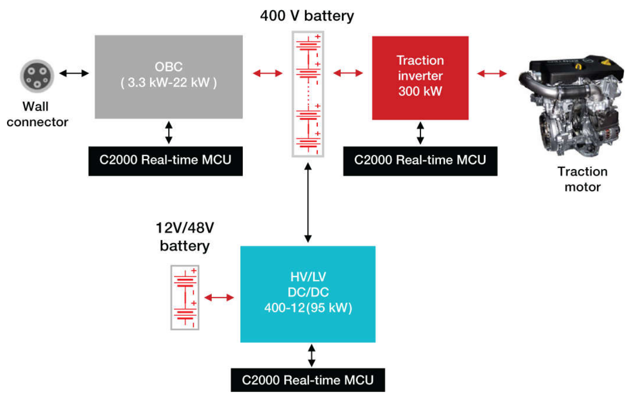

Figure 1. *EV Powertrain System Block Diagram.*

Efficient control and management of the power flow in these systems can be achieved using one or more real-time microcontrollers (MCUs). To save mechanical costs and reduce the size of power electronics, one popular trend is to integrate OBC equipment with the high-voltage to low-voltage DC/DC converter, which can save as much as 10%-20% of board space. However, this adds additional requirements for the real-time MCU, as it need to support more pulse-width modulators (PWMs), more ADCs and allow for multicore processing to manage multiple power stages.

Further, OBCs need to support bidirectional operation for vehicle-to-grid, which result in more complex topology choices that necessitate even greater care when selecting an MCU for an OBC. The MCU must include features that:

- Reduce magnetic size and weight by enabling high frequency operation through high resolution control of power converters duty cycle, frequency, deadband and phase-shift.
- Reduce losses by enabling soft-switching schemes that don't compromise efficiency, such as critical mode operation and valley switching.
- Reduce cost by increasing analog integration to reduce the number of external components in the design, such as comparators and digital-to-analog converters (DACs).

The MCU should also be part of a scalable portfolio to support the variety of options when integrating OBCs with the high-voltage to low-voltage DC/DC converter. In this white paper, we will review the typical topologies and challenges for each stage and highlight some of the features of C2000 real-time MCUs to help you solve those challenges.

Totem-pole PFC and CLLLC topology for onboard chargers

Figure 2 shows a 3.3-kW OBC with a totem-pole PFC stage for the OBC PFC and a capacitor-inductor-inductor-inductor-capacitor (CLLLC) stage for the OBC DC/DC converter. A totem-pole bridgeless PFC improves efficiency by lowering the number of power devices in the current path, while enabling bidirectional operation (compared to a conventional bridge-based PFC). Implementations of totem-pole bridgeless PFC were previously limited to lower power levels only because the inherent body diode in silicon power metal-oxide semiconductor field-effect transistors was susceptible to high reverse-recovery losses under hard switching. With no such body diode within its structure, GaN power switches such as the LMG3410R050 from Texas Instruments have now made it practically feasible to implement multikilowatt totem-pole bridgeless PFC power supplies. Since GaN devices feature low output capacitance (Coss), they can be operated at high frequencies (100 to 200 kHz), which further allows using smaller inductor and thus shrinks the size of the passive components required in the totem-pole PFC converter.

During dead time, however, third-quadrant operation in GaN switches results in additional losses that a real-time MCU needs to optimize by regulating the dead time precisely. C2000 real-time MCU type 4 PWMs enable features such as high-resolution dead time, which can regulate the deadband to 150 ps of resolution. As an example, for a 100-kHz totem-pole PFC, the loss savings with dead-time optimization is 1 W. As the designers reduce the inductor size further by increasing the switching frequency to 1MHz and employing control techniques such as Critical Mode PFC, the power loss savings can be as high as 10W, thus making optimization of third quadrant losses a critical feature, for which precise and accurate control of the dead time if required.

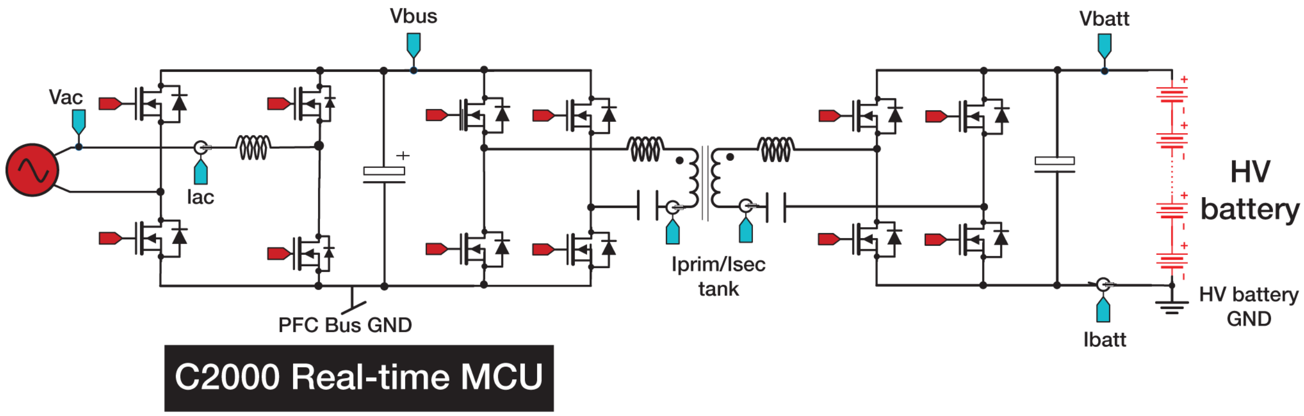

Figure 2. *OBC Power Stage with Single-phase PFC and Isolated DC/DC Stage.*

Peak current mode control for high-voltage to low-voltage DC/DC converters

Looking at the OBC DC/DC stage, an isolated DC/DC converter such as CLLLC is a popular choice as it has an extended zero voltage switching (ZVS) range that provides soft-switching capability to enable higher switching frequency which enables smaller magnetic size. Further, a synchronous rectification scheme (Figure 3) can enable efficiency improvements of as much as 2%, but this scheme is challenging to implement and often requires external circuitry. The integrated comparator subsystems on C2000 MCUs enable the implementation of synchronous rectification without external components such as DACs, comparators or logic gates. Furthermore, the Type-4 PWM allows additional blanking windows during PWM periods and can latch the current crossing events to add robustness to the synchronous rectification scheme, thus adding noise resiliency to the implementation.

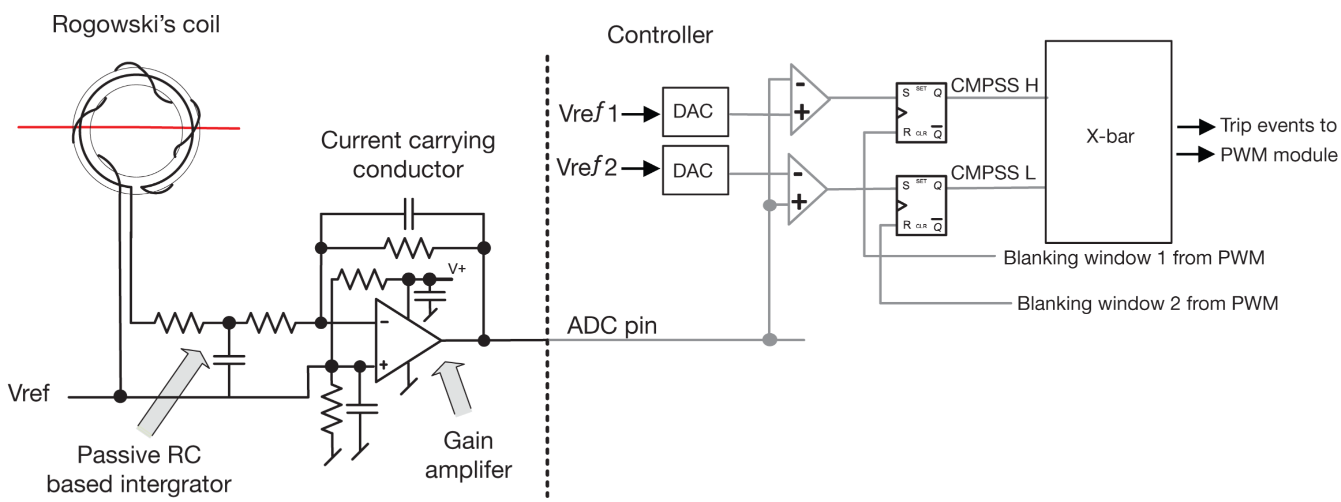

Figure 3. *Active Synchronous Rectification Scheme with On-chip Resources for High-frequency Converters.*

Looking at the high-voltage to low-voltage DC/DC converter, phase-shifted full bridge (PSFB) is a typical topology used. Peak current-mode control eliminates the need for an expensive DC blocking capacitor. The primary challenge in implementing peak current-mode control is that it can lead to system instability, as shown in **Figure 4**. Slope compensation is added to the peak current reference point, to avoid this instability and is typically implemented in analog.

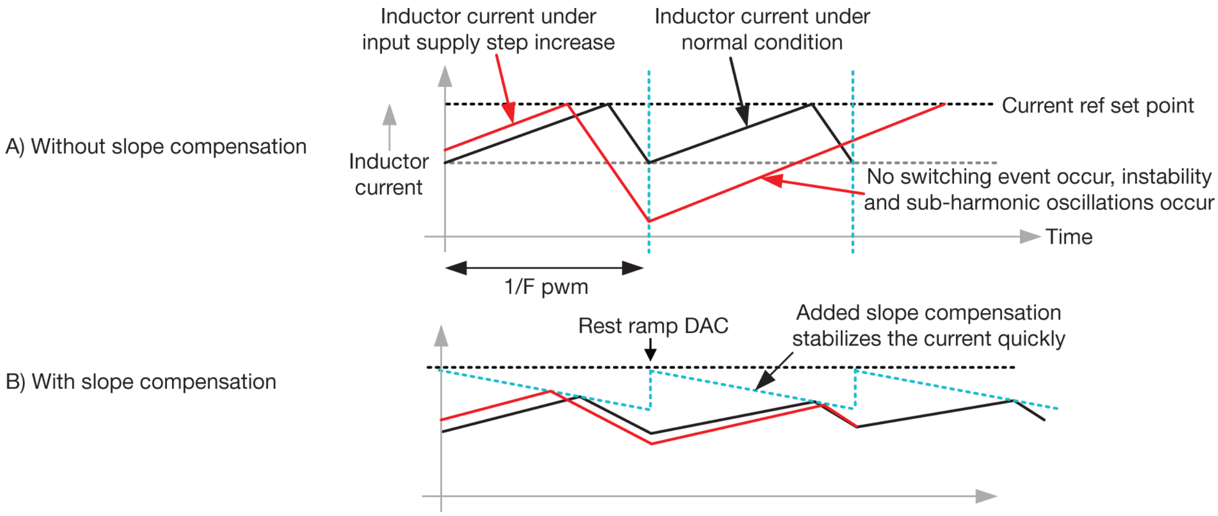

Figure 4. *Peak Current-mode Control Implementation with Slope Compensation.*

The advanced analog integration in the C2000 real-time MCU comparator subsystem enables achieving this advanced control with a digital controller. Additionally, Type-4 PWM features such as inserting deadband when a peak current event occurs allows the digital controller to generate complimentary PWM. This allows the change of deadband under different line and load conditions to maintain soft switching. Digital control also enables additional functions such as precharging the traction inverter bus using the high voltage to low voltage DC/DC converter, which can eliminate the need for external precharge resistors and further reduce components in the powertrain.

Scalable portfolio of real-time MCUs for onboard chargers

OBCs range from 3.3 kW for plug-in hybrid EVs to 6.6 to 22 kW for EVs. Popular architectures for 3.3- to 6.6-kW OBCs include totem-pole PFC and CLLLC. **Table 1** lists the different real-time MCU choices available based on the system architecture, as well as integration options.

	Minimun resource requirements			Typical real-time MCU option		
	PWMs	ADCs	MIPS	Separate controller	Single controller for OBC, separate for HV/LV DC/DC	Single integrated controller
3.3kW/6.6kW OBC PFC stage (totem-pole PFC)	2	5	70	F280025	F280049	F2837S
3.3kW/6.6kW OBC DC/DC converter (CLLLC)	8	5	50	F280025	F280025	
3kW High-voltage to low-voltage DC/DC converter	6	5	40	F20025		

Table 1. *Real-time MCUs for 3.3- to 6.6-kW OBCs and High-voltage to Low-voltage DC/DC Systems.*

For 11kW and higher OBCs, one approach is to stack three 3.6-kW chargers (which are topology-wise similar to 3.3-kW chargers); this is referred to as the modular OBC approach. It's also possible to design additional 22-kW chargers by stacking 11-kW chargers or increasing the power rating by paralleling or by selecting different field-effect transistors (FETs). Another approach to 11kW uses a three-phase PFC front end with some derating for single-phase operation.

The approach selected by the OEM can vary based on geographic region. For example, in the U.S., single phase is more readily available, so a modular approach is popular. In Europe or Asia, where three phase is more readily available, a three-phase PFC can offer higher density and lower costs, since the system requires fewer power devices and switches. To address this wide range of power levels, look for a scalable controller portfolio that can not only handle advanced topology control but also enable integration. The C2000 MCU portfolio (**Table 3**), ranging from low to mid to high end devices, enables the system implementation options in **Table 1** and **Table 2**.

	Minimun resource requirements			Typical real-time MCU option	
	PWMs	ADCs	MIPS	Separate controller	Single integrated controller
11kW modular OBC (PFC plus DC/DC converter)	10	10	120	Three F280049s	F28388D
3kW high-voltage to low-voltage DC/DC converter	6	5	40	F280025	F28388D
11kW OBC PFC stage (T-Type)	12	8	50	F280025	
11kW OBC DC/DC stage (two DC-DC converters, 5.5kW each)	16	8	100	F280049	

Table 2. *Real-time MCUs for 11-kW and Higher OBC and High-voltage to Low-voltage DC/DC Converter Systems.*

Device	PWM	ADC	MIPS
F280025	14	16	100
F280049	14	21	200
F28377D	24	24	800
F28388D	32	24	925

Table 3. *C2000 Real-time MCU Portfolio.*

In the modular approach (which stacks three single-phase chargers to reach 11 kW), each module is designed for 3.6 kW, works with a single-phase AC input, and typically has a single-phase PFC stage and a DC/DC stage (**Figure 5**). The high-voltage and low-voltage DC/DC converter connects to the high-voltage battery on one end and the 12-V battery on the other. The existence of multiple isolation planes in the system allows for the design of a single controller for each phase, with a separate controller (using the F280049) or a single controller (such as the F28388) controlling all three stages of the OBC. The F280025 can also control the high-voltage to low-voltage DC/DC converter, as it provides the necessary advanced analog integration to control the phase-shifted full-bridge power stage.

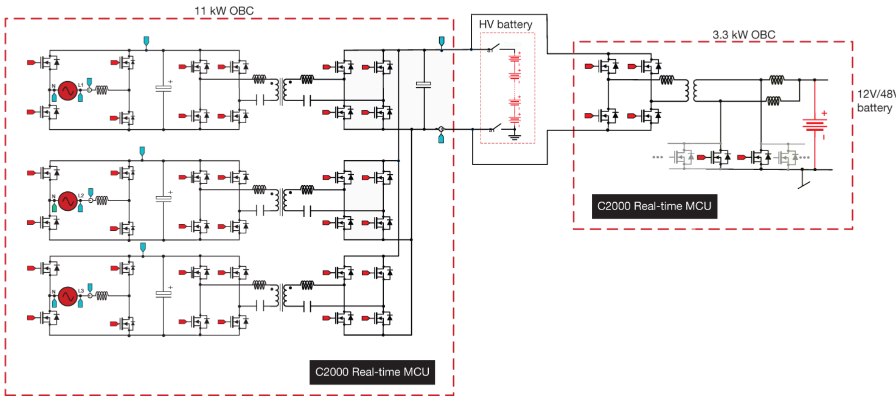

Figure 5. *11-kW OBC with 3.6-kW Stacked Chargers and a High-voltage to Low-voltage DC/DC Converter.*

If the power stage is not modular, you can control the entire system using a single controller. **Figure 6** shows one such example, using a T-type three-phase PFC and an interleaved dual active bridge (DAB) converter for the OBC. (**Table 2** listed several MCU choices for this system.) The F28388D device from the C2000 real-time MCU family can control all of the power electronics in the system. As OEMs optimize these systems, concepts such as "one-box" are gaining momentum, where the OBC and high-voltage to low-voltage DC/DC converter are housed in the same enclosure. The one-box concept opens up additional options by using multiport converters that share the DC/ DC stage between the OBC DC/DC stage and high-voltage to low-voltage DC/DC converter.

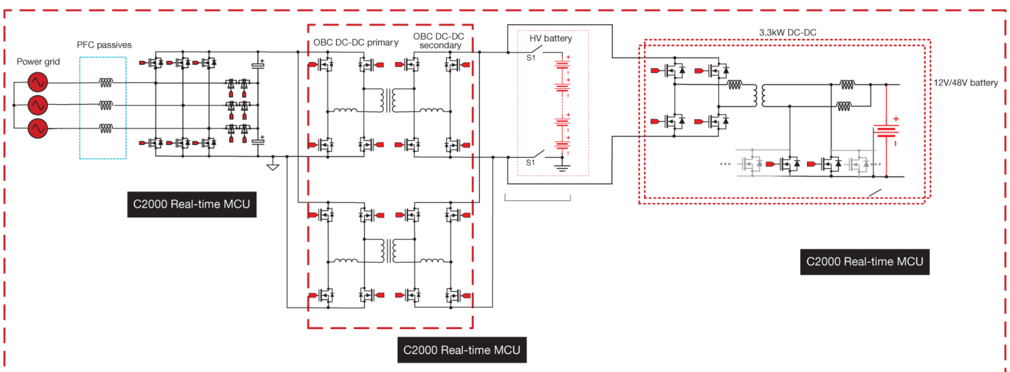

Figure 6. *11-kW OBC plus a High-voltage to Low-voltage DC/DC Converter Controlled Using the F28388D.*

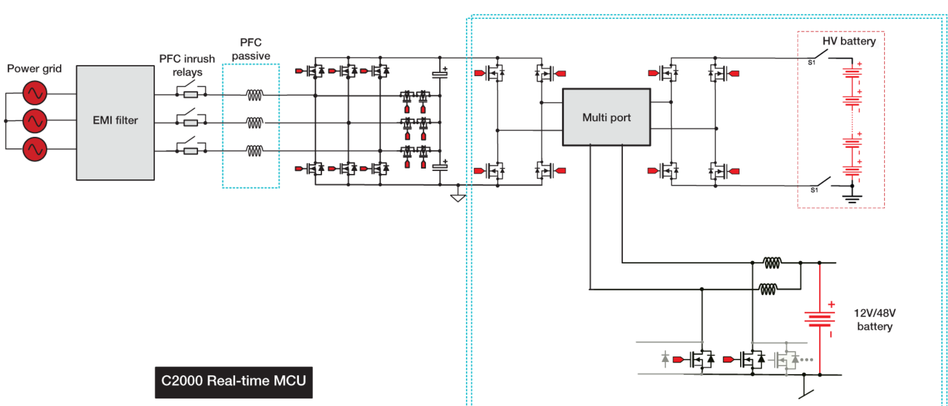

Figure 7. *An 11-kW OBC plus High-voltage to Low-voltage DC/DC Converter Using a Multiport Scheme Controlled by the F28388D.*

Now that a single controller is controlling all of the stages, further optimizations become possible. Figure 7 shows the use of a multiport converter, which reduces the number of switches/high-voltage FETs required by 16%.

Conclusion

As OEMs and Tier-1s push the limits of efficiency and power density, the need arises for real-time controllers that are scalable and can enable advanced topologies and integration options. The device capabilities built into C2000 MCUs enable system designers to achieve higher switching frequencies while maintaining high efficiency, thus reducing system size and cost. The C2000 real-time MCU portfolio includes modular to fully integrated solutions, along with reference designs and software for advanced topologies such as CLLLC, DAB, totem-pole PFC, Vienna rectifier, T-Type PFC and phase-shifted full bridge (PSFB).

These tools and resources can accelerate the design and development of power converters for EV applications such as OBC and high-voltage to low-voltage DC/DC converters.

Additional resources

- C2000 real-time MCUs
- GaN power devices

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