

# A Closer Look at the On-Board Charger

The development of the second-generation module for the Chevrolet Volt.

**B**ATTERY-ELECTRIC VEHICLES AND PLUG-IN hybrid-electric vehicles typically include an on-board-charger (OBC) module. The OBC converts ac power from the electrical grid to dc power that is used to charge the vehicle's propulsion battery. The OBC design supports overall vehicle objectives, including high-efficiency, performance, reliability, utility, and affordability. This article describes General Motor's (GM's) objectives for development of the second-generation (Gen2) OBC introduced in the 2016 Chevrolet Volt.

## Design Objectives

The OBC is a relatively new automotive component that has not yet been optimized over generations of development. At the start of development of GM's Gen2 OBC, significant improvements were still possible even without groundbreaking technological advancement. Based on GM's experience with the first-generation Volt, the following focus areas were established for the Gen2 OBC: 1) efficiency, 2) power density, and 3) complexity reduction.

Digital Object Identifier 10.1109/MELE.2016.2644265  
Date of publication: 7 March 2017



The efficiency of the charging system directly effects overall vehicle efficiency. Energy losses in the OBC correspond to ac grid energy that is consumed but does not contribute to charging the battery. Reducing OBC losses also reduces the work required of the cooling system during battery charging, which improves the overall charging system efficiency.

Increased power density is also desirable. Car makers must integrate the OBC into electric vehicles without affecting the usable space for the customer or significantly increasing the vehicle mass because the vehicle being small in size helps reduce the vehicle mass. It can also reduce investment if the OBC can be reused in multiple vehicles without the need for design changes to facilitate vehicle integration.

Finally, reliability of the OBC is critical for an electric vehicle. To support increased reliability, emphasis was placed on reducing the number of components and eliminating the least reliable components within the OBC.

Complexity of the vehicle control interface and diagnostics was also reduced.

### Benchmarking

Prior to setting design targets for the Gen2 OBC, GM evaluated competitors' electric vehicles and prototype OBCs provided by potential suppliers. The measured efficiencies of six OBCs (identified as A–F) are shown in Figure 1. Efficiency varies with several parameters, including input voltage, output voltage, power, and temperature. Thus, efficiency comparisons were made under a common operating condition. Figure 1 also shows the efficiency of GM's Gen2 2016 Volt OBC.

Figure 2 provides benchmarking data for volume-power density (kW/liter) and mass-power density (kW/kg). The volume-power density was calculated using the OBC housing volume while excluding features that protrude out from the housing, such as connectors, coolant fittings, or attachment feet. Figure 2 also shows the power density of GM's Gen2 Volt OBC.

### Specification

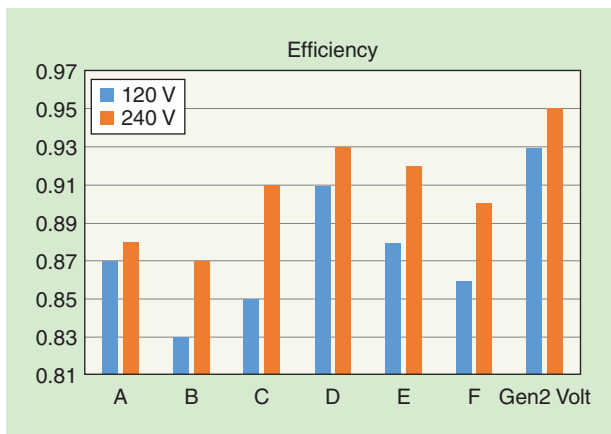
Design objectives were established based on benchmark data and supplier input. Efficiency and power density requirements were set at a level that would insure best-in-class performance at the start of production and remain competitive through the expected production life of the OBC. The input voltage range allows compatibility with the global ac power grid. Current and power levels were selected to meet the target time to fully charge the battery pack (Table 1).

### Efficiency

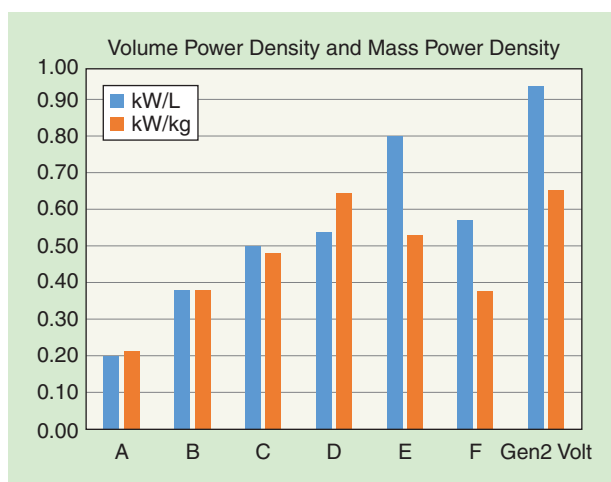
An ideal power converter would achieve 100% efficiency. Real converters include many loss mechanisms and cannot achieve this goal. Power-converter design aims to minimize losses while simultaneously satisfying other objectives. In a power converter, power flows from input to output through a series of components that are involved in transforming the power into the desired form. For example, the OBC converts ac grid power to dc power at the required voltage to charge the propulsion battery. The components required to



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**Figure 1.** The efficiency benchmarking data.



**Figure 2.** The volume-power-density and mass-power-density benchmarking data.

transform the power are of two types. The first type of component includes linear reactive components including inductors, capacitors, and transformers. These components are used for intermediate energy storage and filtering. The second type is a nonlinear electronic switch. These switches are involved with commutating current in the power conversion circuit. Control circuits in the OBC actuate the switches at frequencies in the range of 30 kHz to greater than 100 kHz. Higher frequency operation enables smaller size for reactive components; however, it also increases losses that occur during each switching cycle. The arrangement of the two types of components is generally called a topology. Several topologies can achieve the desired output, with each topology having advantages and disadvantages.

### Topology

Presently, most OBCs include two power converters. Input power initially goes to an ac/dc converter. Then this converter transforms ac voltage to pulsating dc voltage and boosts the voltage to an intermediate value (typically 400 V). The second converter is an isolated dc/dc converter, and a

**TABLE 1. The OBC specification.**

Input voltage	85–265 V/45–65 Hz
Input current	16 A
Output voltage	200–430 V
Output current	13 A
Efficiency (full power)	93% (120-V input)/95% (240-V input)
Output power	3.65 kW
Power density	0.65 kW/kg
Volume power density	0.95 kW/L

large capacitor between the two converters is required to filter the ac grid frequency. The dc/dc converter transforms the intermediate voltage to the final output voltage required for battery charging. Figure 3 shows the specific topologies selected for the 2016 Volt OBC.

### Front-End Converter Topology

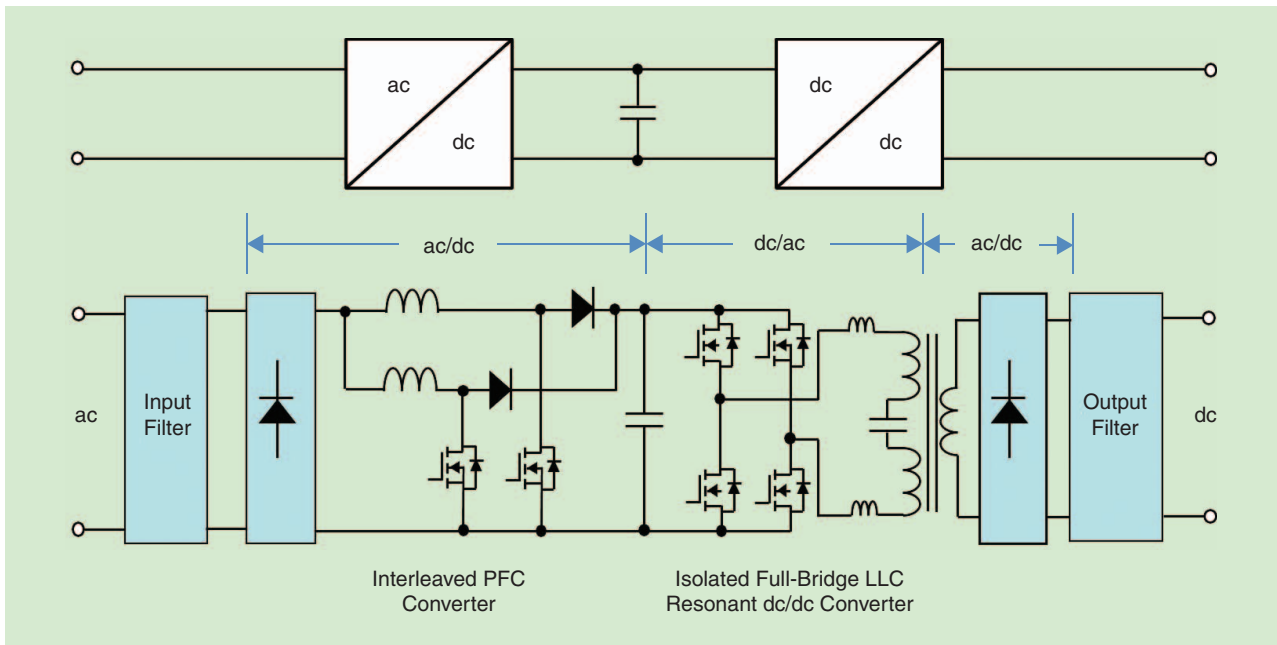
The front-end (ac/dc) converter rectifies ac grid voltage and boosts it to an intermediate voltage (approximately 400 V). International standards require the OBC to maintain a high-power factor and limit harmonic currents at the ac mains. Multiple topologies are suitable for the required power range. The topologies were compared to find the combination of efficiency, size, electromagnetic interference (EMI), reliability, and cost that were best suited to GM's goals.

Two topologies with desirable attributes for an OBC were considered. One topology, as shown in Figure 4, includes a diode bridge and interleaved power-factor-correction (PFC) boost converter, which is the most conventional design. An alternative topology is the bridgeless PFC boost converter shown in Figure 5.

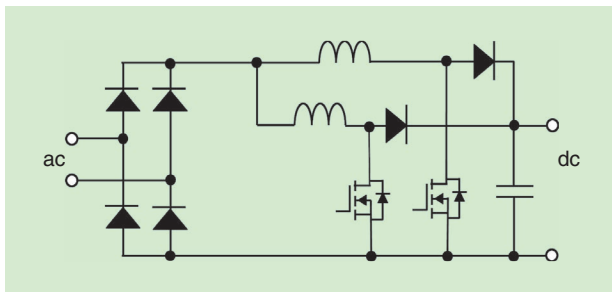
In the conventional interleaved topology, two parallel continuous-conduction-mode boost converters operate 180° out of phase. This interleaving reduces the input ripple because currents in the two inductors partially cancel each other. Interleaving effectively doubles the current ripple frequency and thus reduces the size of the components in the input filter. GM's benchmarking indicated this topology was the most popular front-end converter for automotive OBC applications. As implemented in the 2016 Volt OBC, it achieves an efficiency of 97.8% when operating with 240-V ac input voltage and 16-A current.

The bridgeless PFC topology was investigated due to its potential to provide higher peak efficiency. However, the bridgeless design has disadvantages compared to the conventional design. The ac line voltage is floating relative to the PFC ground. This complicates the voltage measurement because a simple voltage divider circuit cannot be used. Instead, an isolated voltage-sensing solution containing a low-frequency transformer or optical coupler is required. A second disadvantage is that





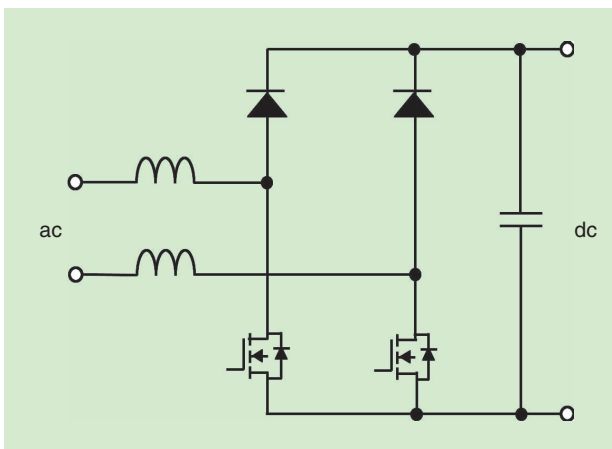
**Figure 3.** The overall topology selected for OBC.



**Figure 4.** The conventional interleaved PFC topology.

**TABLE 2. The front-end converter topology comparison.**

	Interleaved PFC	Bridgeless PFC
Efficiency	97–98%	98%
Voltage sensing	Simple	More complex
Current sensing	Simple	More complex
EMI	Smaller filter components	Larger filter components



**Figure 5.** The bridgeless PFC topology.

current measurement is more complicated. The conventional PFC design allows current to be monitored with a shunt resistor in the return current path. However, monitoring current with a single shunt resistor is not feasible for the bridgeless converter because it has more than

one return current path. Instead, a current transformer or hall-effect current sensor is typically used at the input port. Finally, the bridgeless design leads to increased common mode noise, which can be difficult to filter. These drawbacks led to the selection of the conventional interleaved PFC topology. Table 2 compares the front-end converter topologies.

### Output Converter Topology

The output converter transforms the intermediate dc voltage to the required output dc voltage. Multiple topologies are suitable for this converter, and the topologies investigated were the following: 1) phase-shifted full-bridge (PSFB) converter, as shown in Figure 6, and 2) LLC resonant converter, as shown in Figure 7.

GM's benchmarking indicated the PSFB topology was the most popular design for automotive OBCs. This topology uses fixed frequency pulsewidth modulation (PWM) switching control, and a delay is introduced between the turn-on commands of diagonal switches. This switching technique makes use of parasitic circuit elements to

facilitate zero-voltage switching (ZVS) at turn-on. Switching power loss occurs when current flow is initiated while a large voltage is present across a switch. ZVS avoids this switching loss by creating a condition with the voltage near zero when current flow is initiated.

The resonant LLC topology was not commonly used in OBCs when development of the 2016 Volt OBC started. The design methodology for LLC converters was not as well understood as the methodology for the PSFB converter, which is one reason why the resonant LLC topology was not as popular. However, resonant conversion provides

**Resonant conversion virtually eliminates switching losses.**

benefits compared to the PSFB topology, because it virtually eliminates switching losses by enabling ZVS and zero-current switching throughout the operating range. The LLC topology is able to achieve 97.7% efficiency in the 2016 Volt OBC when operating at

400-V output and 100% load. It also enables higher power density and lower EMI compared to PWM control. Figure 8 illustrates a typical voltage gain characteristic of an LLC resonant converter.

The converter gain is a function of switching frequency instead of duty cycle. Switches are operated at a 50% duty cycle while providing small dead time between the commutations of complementary same-leg switches to achieve ZVS. The LLC resonant converter topology was selected due to its benefits when compared to the PSFB topology. Table 3 compares the output converter topologies.

Total OBC efficiency is determined by losses in the front-end converter, output converter, other components in the power flow path, and control circuits. Figures 9 and 10 show overall measured efficiency for the OBC operating with an input voltage of 120 V and 240 V, respectively. The OBC achieves the target of 95% efficiency for 240-V operations at full power and reaches 96% when operating at lower power.

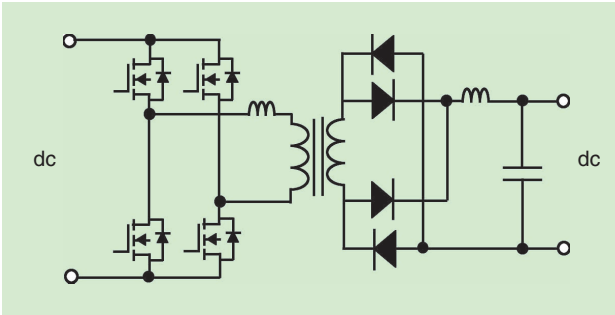


Figure 6. The dc/dc PSFB topology.

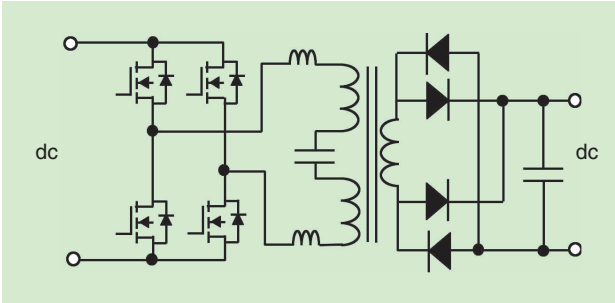


Figure 7. The dc/dc full-bridge LLC resonant topology.

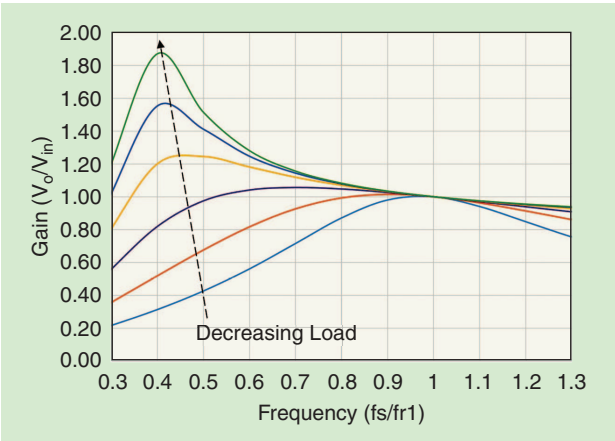


Figure 8. The LLC resonant converter voltage gain versus normalized frequency. fs: switching frequency; fr: resonant frequency.

### Power Density

Compact design was important to maximize the potential for reusing the OBC in multiple vehicle platforms. Reuse allows amortization of the development, validation, and tooling expenses over larger production volumes. Figures 11 and 12 show the OBC module, and the volume of the housing (not including connectors, coolant ports, or mounting feet) is 4.0 L. This volume is 50% smaller than the OBC used in GM's first-generation Volt even though the maximum power capability is 7% higher. Consequently, significantly improved power density was achieved without the need for pioneering technologies. Careful attention to component layout resulted in high-utilization of the available space in the housing.

The coolant channel was also designed to minimize OBC height. Most OBC's examined by GM had cooling plate thicknesses that were uniform across the module, and that design does not achieve minimum possible

TABLE 3. The output converter topology comparison.		
	PSFB	LLC Resonant
Efficiency	94–95%	97–98%
Control	Simple	More complex
Size	Larger	Smaller
EMI	Larger filter components	Smaller filter components

height. The coolant channel in the Gen2 OBC (see Figure 13) has indentations that allow taller components, such as the transformer and electrolytic capacitors, to be recessed into the cooling plate. Thus, coolant flows next to and below the components rather than only below. This design choice allowed reduction of the OBC height and improved component cooling. However, one disadvantage of this design is that coolant flow resistance increased because of the additional bends compared to a U-shaped channel.

All power metal-oxide semiconductor field-effect transistors and diodes were located around the perimeter of the OBC housing (see Figure 14). Mounting the power switches linearly around the perimeter eliminated the need for coolant to flow under a large portion of the module to reach all components that require cooling.

### Complexity Reduction

Reduced complexity was pursued as a strategy to improve reliability. Compared to GM's first-generation OBC, the Gen2 has fewer components and less complex vehicle interface and diagnostics, which improves the predicted reliability. Although hard to predict, reduced diagnostic software complexity should also improve reliability as a result of fewer opportunities for design issues.

GM's first-generation Volt OBC included a low-voltage (LV) output. LV power is needed by modules associated with propulsion battery charging control, thermal management, and displays. Without a source of LV power, the 12-V battery would become discharged during the hours required to charge the propulsion battery. The first-generation OBC design included multiple dc/dc converters to supply high-voltage (HV) (200–430 V) and LV (12 V) output power. However, the vehicle also included a separate dc/dc module that was able to transform HV power to LV power during drive mode. This dc/dc converter is called the *auxiliary power module (APM)*. For the Gen2 OBC design, the LV output was eliminated. Instead, the APM provides LV power during both the drive mode and charging mode.

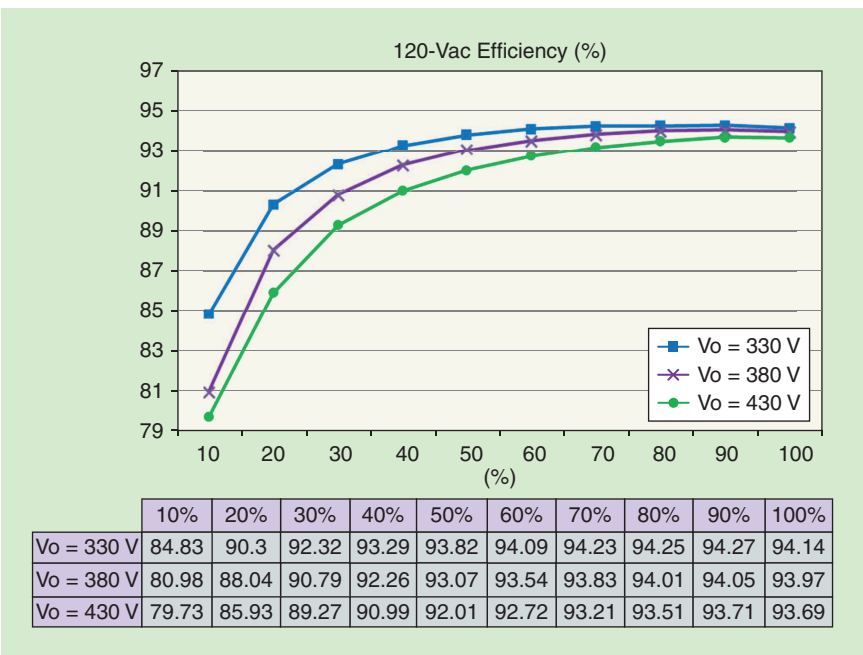


Figure 9. The OBC efficiency with an input voltage of 120 V.

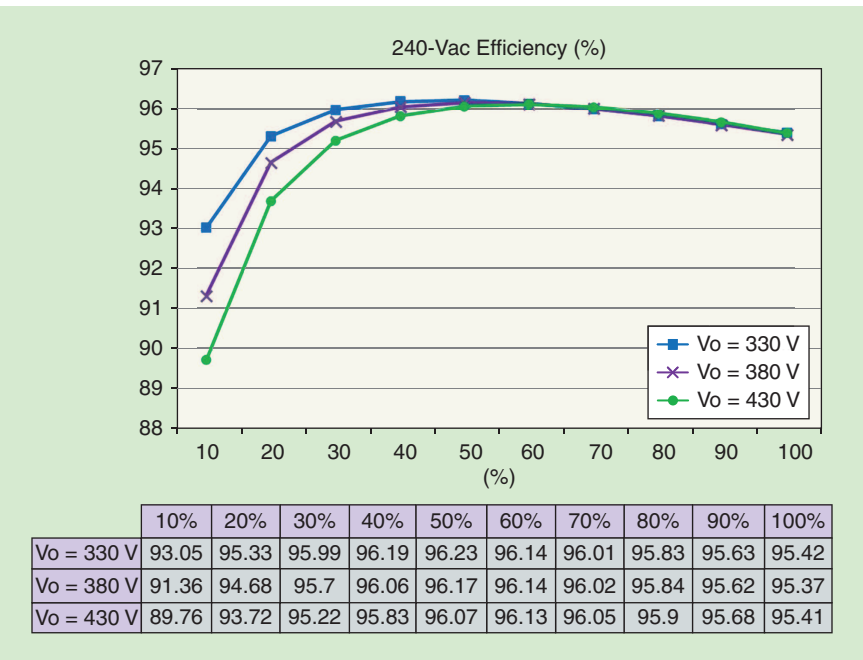
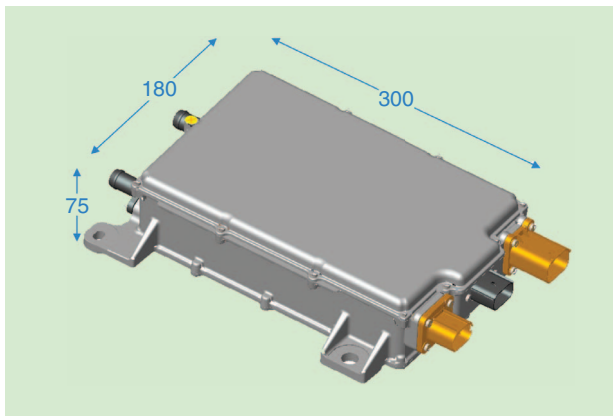
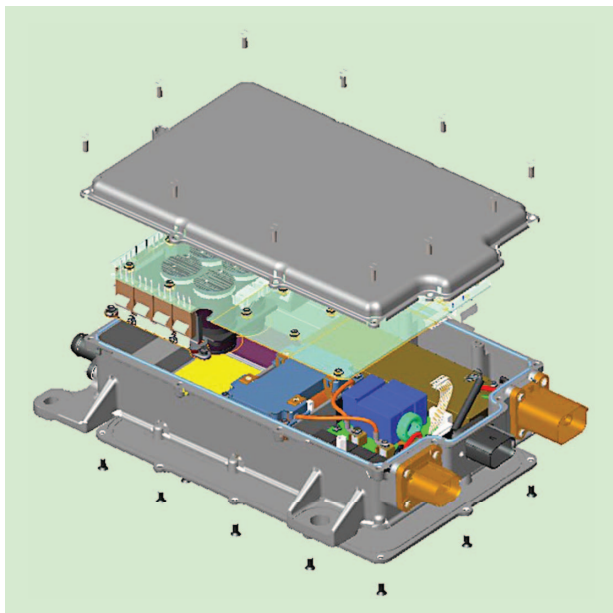


Figure 10. The OBC efficiency with an input voltage of 240 V.

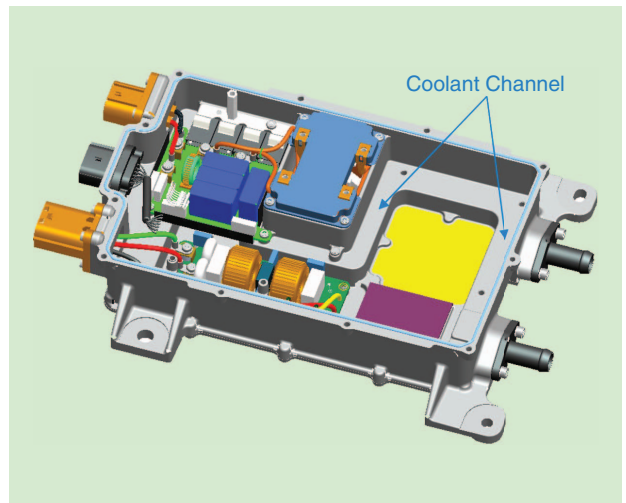
Diagnostic software is another area where GM achieved complexity reduction. The first-generation OBC software was able to detect 78 distinct failures within the OBC. However, the OBC was not serviceable at the dealer, so all OBC failures resulted in replacement of the OBC. The detailed diagnostic information was generally not needed to identify the root cause of OBC failure. Thus, this complex approach created opportunities for diagnostic design flaws but did not provide significant benefits. The number of diagnostics has been reduced in the



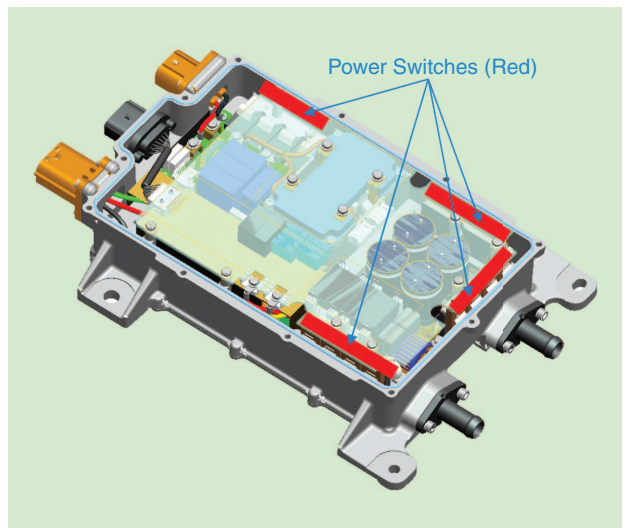
**Figure 11.** The OBC for the 2016 Chevrolet Volt.



**Figure 12.** The OBC exploded view.



**Figure 13.** The OBC coolant channel.



**Figure 14.** The OBC power switch locations.

Gen2 charging system, and the diagnostic software has been moved from the OBC to the battery management system (BMS). The BMS uses sensor data from the battery and the OBC to evaluate whether the charging system is working correctly. GM developed the BMS software, including the diagnostics, and this approach allows the charging system diagnostics to be reusable. The same software can diagnose all OBCs even if GM uses multiple suppliers. The ability to reuse diagnostic software rather than repeat the development work should reduce potential issues. The reduced number of diagnostic codes supports the goal of improving diagnostic robustness without degrading GM's ability to isolate the root cause of failures.

### Summary

Design objectives for GM's Gen2 OBC included improved efficiency, higher power density, and reduced complexity.

Selection of the resonant LLC converter topology played an important role in achieving GM's efficiency target, and significant improvement in power density was achieved through optimal mechanical layout. Complexity reduction was also achieved by removing functions from the OBC that could be fulfilled by other existing modules.

### For Further Reading

D. Cesiél and C. Zhu, "Next generation 'Voltec' charging system," presented at the SAE 2016 World Congr. Exhibition, Tech. Paper 2016-01-1229, 2016. doi: 10.4271/2016-01-1229.

### Biographies

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