

Power Dense and Robust Traction Power Inverter for the Second-Generation Chevrolet Volt Extended-Range EV

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ABSTRACT

The Chevrolet Volt is an electric vehicle with extended-range that is capable of operation on battery power alone, and on engine power after depletion of the battery charge. First generation Chevrolet Volts were driven over half a billion miles in North America from October 2013 through September 2014, 74% of which were all-electric [1, 12]. For 2016, GM has developed the second-generation of the Volt vehicle and "Voltec" propulsion system. By significantly re-engineering the traction power inverter module (TPIM) for the second-generation Chevrolet Volt extended-range electric vehicle (EREV), we were able to meet all performance targets while maintaining extremely high reliability and environmental robustness. The power switch was re-designed to achieve efficiency targets and meet thermal challenges. A novel cooling approach enables high power density while maintaining a very high overall conversion efficiency.

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INTRODUCTION

General Motors (GM) was the first in modern days to offer complete electrification when its Battery Electric Vehicle (BEV) EV₁ was introduced in 1996 [3]. Subsequently GM is enhancing level of electrification [2] by introducing hybrid electric vehicle (HEV), plug-in HEV (PHEV), Extended Range EV (EREV) 1st Generation VOLT [5,8] and most recently 2nd Generation VOLT. Optimal design of TPIM power electronics is one of the enablers to achieve aggressive fuel-economy, performance, reliability, cost and mass targets for these electrified vehicles. EREV, first introduced by GM [5], has full functionality as an EV, better electrification than PHEV and blended operation of gas and electricity as necessary. EREV electric drive system contains two PM motors that are commuted by two traction inverters, PIM-A (power inverter-A), PIM-B (power inverter-B) and an oil pump motor run by a third inverter. All these three inverters are contained in one package named TPIM situated between electric motors and battery.

A comprehensive analysis, design and validation plan was tailored to the 2nd Generation VOLT TPIM. Worst-case analyses were performed and confirmed with a comprehensive early design demonstration. Thermal measurements were made to understand the effectiveness of cooling design and to map peak temperatures and gradients predicted analytically. In addition, design failure modes and effects analysis were used to refine the design. This paper focuses on system architecture, power electronics component design optimization, efficiency, size, cost, performance and safety of 2nd Generation VOLT TPIM. Mechanical interfaces, assembly features and environmental robustness of the TPIM are also presented in this paper. Section-II describes propulsion, electric drive and HV system requirements overview. Section-III presents power electronics design optimization, power stage selection criteria, TPIM performance, thermal robustness and efficiency metrics. Mechanical orientation, stiffness/ vibration robustness features of TPIM and transmission assembly features, coolant interface are discussed in Section-IV. Section-V compares features between 1st Generation VOLT and 2nd Generation VOLT TPIMs. System and TPIM level test results are included in Section-V. Figure 1 shows 2nd Generation VOLT HV components vehicle layout.

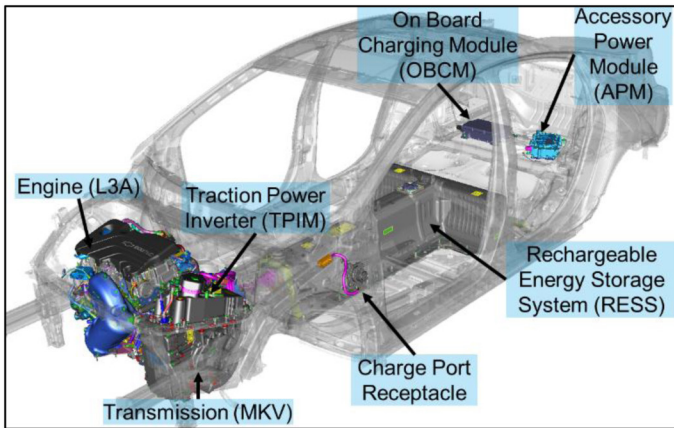


Figure 1. 2nd Generation VOLT HV Power Electronics Components Vehicle Layout.

SYSTEM AND REQUIREMENT OVERVIEW

2nd Generation VOLT electric drive system has very aggressive targets for cost, all electric range, fuel economy and vehicle tractive performance where TPIM power density, efficiency, thermal strength and structural robustness, mounting on transmission manifold, elimination of AC cables are some of the major contributors to meet this target.

Improvement Comparison

Table 1 shows TPIM high level requirements comparison between 1st Generation VOLT and 2nd Generation VOLT. In 2nd Generation VOLT architecture, realization of a better power flow between engine and two electric motors reduces peak simultaneous AC power kVA by 19% and maximum phase current on PIM-B (power inverter-B) by 24% while increasing PIM-A current by 48%. Better understanding of the electric drive system, interdisciplinary nature of power electronics technology are among the design considerations to achieve projected vehicle EV range increase of 30%, charge sustaining (CS) label fuel economy increase of 10% and improved vehicle performance both as an electric vehicle and in extended range mode, compared to 1st Generation VOLT [12]. 2nd Generation VOLT TPIM has improvements in efficiency, performance, power density, mass and volume as shown in Table 2. Below is a list of main design targets for 2nd Generation VOLT TPIM -

- Low system cost:** Understand vehicle drive profiles and mechanical integration of drive unit. Efficient power flow between two motors, lower part counts, elimination of AC cables and less assembly labors
- Improved Robustness:** Improved interconnect and packaging technique to ensure durability, robustness.
- Fuel economy and electric range:** State of the art silicon and module technology, electric drive system efficiency optimization.

- Drive quality:** Understanding worst-case drive profiles, balancing between performance and tractive efforts.
- Safety integrity:** Protection and sensor circuit design, microprocessor selection and software design for fault protection, diagnostic and calibration schemes.

Table 1. TPIM High Level Requirement Comparison.

PARAMETERS	VOLT-1 TPIM		VOLT-2 TPIM	
	PIM-A	PIM-B	PIM-A	PIM-B
Maximum Phase Current (Arms)	220	430	325	325
Maximum AC Power (kW)	55	111	48	87
Max Fundamental Frequency (Hz)	800	950	800	1200
Continuous Phase Current (Arms)	150 Arms (Inverter-A and Inverter-B Each)			
HV DC Voltage	430 Volt (Peak) , 360 Volt (Nominal)			
Coolant Temperature & Flowrate	75° C at 10 liter/ minute			
Max Simultaneous AC Power (kVA)	221 kVA		180 kVA	
TPIM Mounting/ AC Cables	Body/ External AC Cables		Transmission/ Internal Bus	

Table 2. TPIM Feature and Improvement Comparison.

TPIM and System Improvement Metric	VOLT-1 TPIM	VOLT-2 TPIM
		
TPIM Volume: Liter	13.1	10.4
TPIM Mass: Kg	14.6	8.3
Max. Simultaneous Power: kVA	221	180
Gravimetric Power Density : kVA/Kg	43% Improved	
TPIM Power Density : kVA/Liter	2% Improved	
Average Electric Drive System FTP City Efficiency	6% Improved	
Projected Vehicle EV Range	30% Increased	
Projected CS Label Fuel Economy	11% Improved	

Propulsion and Transmission System

2nd Generation VOLT transaxle has gears, clutches, shafts and controllers to execute multiple kinematic modes including electric vehicle operation and charge sustaining hybrid operations. The 2nd Generation VOLT transmission allows the efficient sharing of tractive loads across both electric motors. This load sharing enabled the peak torque requirements for the PIM-B electric motor to be reduced from the level required on the 1st Generation VOLT. This reduction allows a corresponding reduction in the peak current from the TPIM. Lowering the peak current requirement for each inverter as well as selecting power dense TPIM architecture allows a package size that could be fit into a cavity on top of the transmission as shown in Figure 2 (a).

The transmission internal location for the TPIM simplifies the mechanical integration of the electric drive system into the vehicle that lowers part counts and assembly labors. Figure 2 (b) shows TPIM orientation that is chosen to minimize impact during vehicle crash. Figure 2 (c-d) shows TPIM assembly on transmission and coolant interface implementation.

TPIM arrives at the manufacturing plant as a single component that is bolted into the transmission in a single operation. TPIM Interface to 3-phase AC motor done with ridged bus bars that pass through a cast wall in the transmission case. Coolant interface is done through a gasketed joint. Coolant is routed through the transmission case to an external cooling pipe assembly. The coolant pipe assembly can be unique for each vehicle application to keep the plant interface common for all versions of the transmission.

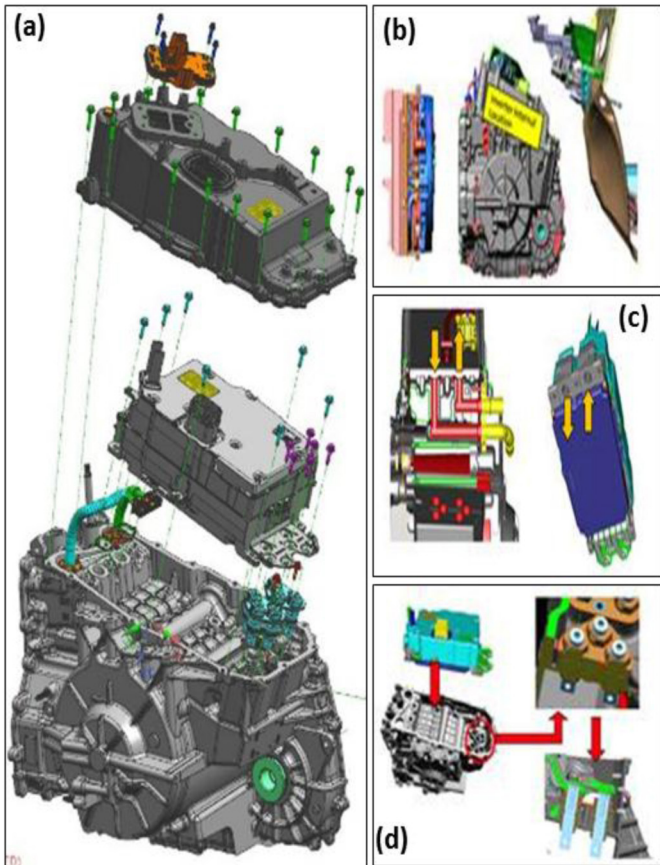


Figure 2. (a) Exploded view of Transmission showing TPIM Assembly (b-d) TPIM Features and Interfaces.

TPIM and Electric Drive System

The TPIM interfaces with HV battery, motors, inverter cooling and the rest of the vehicle electrical systems and controls. The main building blocks of the TPIM are power board, DC bus capacitor, EMI filters, control and gate drive boards, sensors and busbar. The motor controls algorithms are programmed into the control boards. Figure 3 (a) shows the exploded view of the TPIM showing these components. All 12 power switches (Silicon IGBT and Diode for PIM-A and PIM-B) are connected to the heat sink assembly from both sides and they are placed on a specially designed double sided printed board (item 9, 10, 12) with other essential circuits. This board is called “Power Board” and is shown in Figure 3 (b).

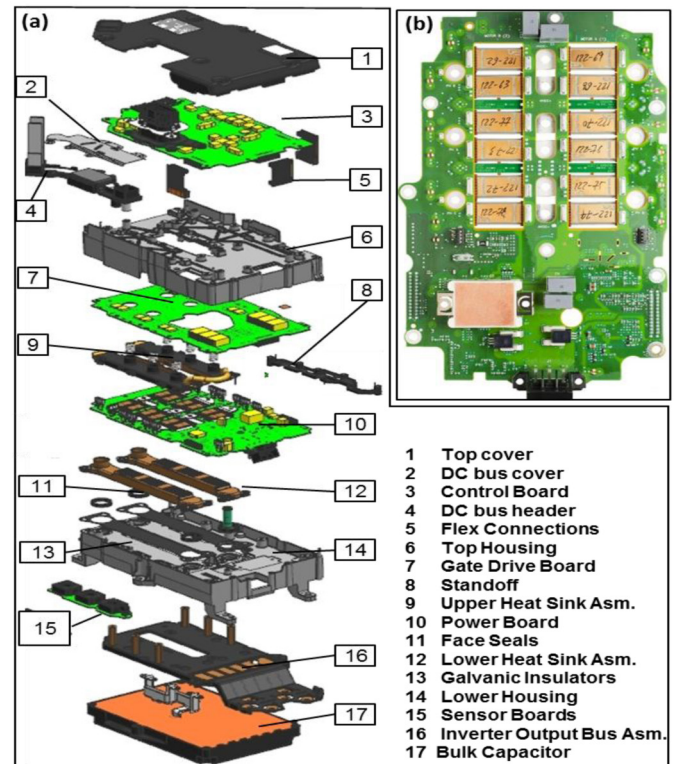


Figure 3. 2nd Generation VOLT TPIM (a) Exploded View and (b) “Power Board” (10).

ELECTRICAL DESIGN OPTIMIZATION

2nd Generation VOLT TPIM power stage has been designed to meet mainly efficiency, performance and durability requirements. Silicon technology, tradeoffs between switching and conduction loss parameters, silicon size and thickness, thermal impedance, loop inductance and PWM switching techniques are carefully crafted to achieve an optimized power module design that meets the high level design target described in System Overview section. To meet high mile-per-gallon target, special attention was paid to achieve high TPIM efficiency for the FTP drive cycles. Figure 4 shows TPIM efficiency for a torque-speed zone that is heavily used for all FTP cycles. As mentioned earlier, better power flow between Inverters, better efficiency (Figure 5) and thermal robustness (will be discussed in next section) enabled, average electric drive system FTP city efficiency improvement of 6%, projected CS label fuel economy increase of 10%, and both ‘Low End Torque’ and ‘High Speed Power’ improvements. Table 3 (a) shows silicon level improvements and some of the attributes of ‘power board’ as compared with 1st Generation VOLT power module. Besides ‘power board’, bulk-capacitor is another expensive and bulky parts on the TPIM that needs to fit inside the inverter package, meet ripple requirement for the HV DC bus and sustain additional thermal stress for this transmission mount TPIM. Table 3(b) shows bulk-capacitor and connector improvements and features.