

The Next Generation “Voltec” Extended Range EV Propulsion System

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ABSTRACT

The Chevrolet Volt is an electric vehicle (EV) with extended-range (ER) that is capable of operation on battery power alone, and on power generated by an on-board gasoline engine after depletion of the battery charge. For 2016, GM has developed the next generation of the Volt vehicle and “Voltec” propulsion system.

Building on the experience of the first generation Volt, the second generation targeted improved all-electric range, improved charge sustaining fuel economy, and improved performance. All of this was to be accomplished while maintaining the EV character of the first generation Volt which customers clearly valued.

This paper describes the next generation “Voltec” system and the realized improvements in efficiency and performance. The features of the propulsion system components, including energy storage, transaxle, electric motors and power electronics, on-board charging, and engine are described and compared with the previous generation. Next, the transaxle powerflow is discussed and operation under typical driving conditions is explained. Finally, system efficiency and performance data, based on component tests, is presented and compared with the previous generation.

This system includes a battery pack with greater energy density, a new transaxle with integrated power electronics and motors, and an engine with optimized displacement, direct injection, and other advanced features.

As a result of these improvements, the second generation Volt vehicle is projected to achieve a 30% increase in EV range, an 11% improvement in charge sustaining label fuel economy, and improved vehicle performance both as an electric vehicle, and in extended range mode.

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INTRODUCTION

The Volt is an electric vehicle with extended range, which can operate with full vehicle performance on battery power alone, without using its engine, so long as the battery pack has sufficient energy and power available. For most owners, the Volt is supplied with electrical energy from the grid through nightly charging, and the engine runs only when a daily drive exceeds EV range or during very cold weather. The second-generation Volt propulsion system, like the first-generation Volt propulsion system, is a fully-capable and efficient EV propulsion system that can integrate engine power to continue driving if EV range is exceeded. Whether the vehicle is operating in electric or range-extended mode, it is designed to provide full capability without compromising speed, hill climbing ability, or performance, and a similarly pleasing driving experience in terms of NVH and smoothness. The second-generation system was designed from a “blank tablet”, with the benefit of experience gained from the Volt and its customers.

The mission of the Volt vehicle is to provide an electric vehicle experience allowing the typical driver to do a majority of their driving electrically, while providing the flexibility of a range-extending engine to allow for longer trips between charges when needed.

The distribution of vehicle trips for a typical customer varies in both driving intensity and distance. In a grid connectable vehicle such as the Volt, the probability that a trip will be completed without requiring engine use depends on three factors: the length of the trip, the driving intensity of the trip, and the frequency of recharging [1,3]. In field usage, frequency of charging has exceeded 1 charge/day for many customers [4]. In terms of vehicle design, EV operation can be maximized by increasing the EV capability as well as the energy available for charge depletion. GM benchmarking of available plug in hybrid vehicles show that the Volt has significantly more all electric range, and a higher level of EV capability than the competitive vehicles studied (Figure 1). For the typical customer, these metrics translate into a vehicle that operates as an EV without starting the

engine for most of their trips, reducing the need for fueling stops and increasing petroleum displacement. Due to its extended range, the EREV vehicle has been found to be as effective at displacing petroleum as a BEV with significantly longer all-electric range [5].

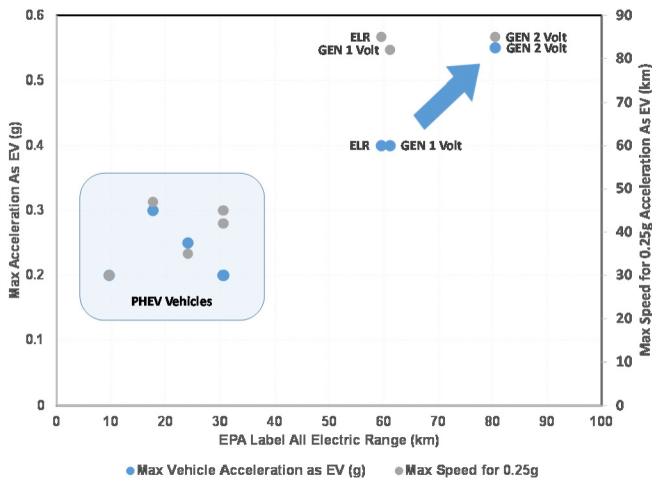


Figure 1. Assessment of EV Drive Metrics

A GM analysis of vehicle data collected from first generation Chevrolet Volts found that Volt vehicles were driven over half a billion miles in North America from October 2013 through September 2014, and that 74% of the miles were all-electric [2]. A previously published study of data collected from a population of Volt vehicles found that average vehicle was driven 41.1 miles a day, with 73.4% of the miles driven electrically [11].

For 2016, GM has developed the next generation of the Volt vehicle and “Voltec” propulsion system. In this paper, the first and second generation vehicles and propulsion systems are referred to as GEN 1 and GEN 2 systems, respectively. As the GEN 2 Volt was developed, GM desired to further enhance the electric utility of the vehicle. To achieve this, key design goals included:

1. Increased all-electric range
2. Increased charge sustaining fuel economy
3. Improved performance
4. Providing smooth, unobtrusive, power on demand regardless of whether the vehicle is operating in EV or range extended mode

The next generation propulsion system advances the Volt concept of all-electric driving with the option of continued charge sustaining driving after battery charge is depleted.

THE 2nd GENERATION VOLT

The systems determining Volt vehicle energy performance can be divided into three primary areas: the vehicle, propulsion system, and charging system, all of which were improved in the second generation vehicle.

A number of changes were made to the vehicle to improve efficiency, including reductions in brake drag and accessory loads. Additionally, due to mass reductions in both the vehicle and propulsion system,

EPA test weight was able to be reduced. These reductions contributed to improvements in EV range, fuel economy in extended range mode, and vehicle acceleration.

The propulsion system was designed with the same emphasis on EV driving, including full acceleration, as the first-generation Volt system. It was designed to be capable of propelling the vehicle on electricity alone under all normal driving conditions. The propulsion system design team was also able to substantially decrease mass and increase fuel economy in extended-range driving, when the engine is used.

Propulsion System

Major components of the propulsion system are the battery pack, the drive unit, and the engine, shown in Figure 2 along with the power flow through the system while driving the vehicle. The battery pack contains cells with sufficient power and energy for everyday EV driving, a heating and cooling system, fuses and contactors, sensors and controls. The drive unit contains two electric motor-generators for propelling the vehicle and other duties, power electronics to supply and control them, a simple system of gears, clutches, and hydraulic controls to combine and deliver the mechanical power from the motor-generators and the engine, and an electric oil pump. The range-extending engine is a four-cylinder, naturally-aspirated direct-injection spark-ignition engine with 1.5 liters displacement and sufficient power to continue normal driving after most of the battery energy has been depleted by EV driving or during conditions when available battery power is low because of extreme temperatures.

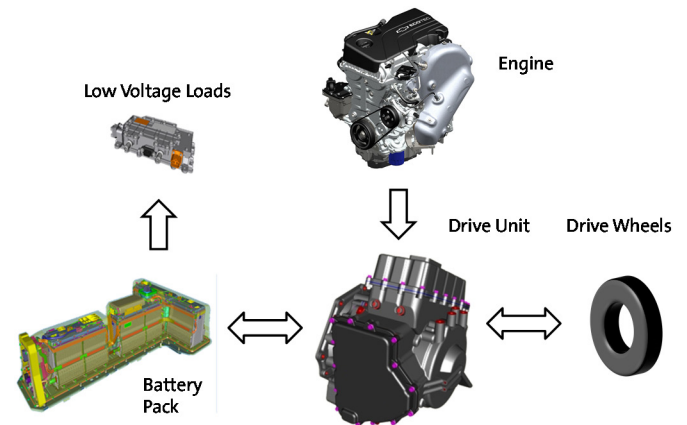


Figure 2. Propulsion System Components

Battery Pack

In order to provide increased vehicle range, battery pack energy in the GEN 2 pack was increased by 12%. The configuration of the pack was changed from 3 to 2 cells in parallel to increase packaging efficiency and improve energy density. With the larger cells, higher energy content, and reduced vehicle mass, the power to energy ratio of the cells was reduced. This allowed further increase in energy density while still providing the required discharge power capability to achieve vehicle performance targets.

A comparison of battery specifications for GEN 1 vs. GEN 2 is given in table 1.

Table 1. GEN 1 and 2 Battery Pack Specifications

	GEN 1	GEN 2
Energy (kW-hr)	16.5	18.4
Maximum Power (kW)	110	120
Pack Capacity (AH)	46.5	52
Configuration	3 parallel, 96 series	2 parallel, 96 series
Cell Chemistry	Li-Ion	Li-Ion
Cell Type	Pouch	Pouch
Mass, Pack (kg)	197	183
Volume, Pack (L)	142	148
Cooling	Liquid	Liquid

Transaxle Configuration and Operating Modes

The propulsion system design team, drawn from General Motors Research and Development (GMR&D), Advanced Engineering, and Product Engineering started by examining all of the known types of electric and hybrid propulsion systems to find the best type for the second-generation Volt. In all, over fifty different types of electric-based propulsion based on both EV and hybrid electric vehicle (HEV) development were identified and evaluated. About half of these were chosen for energy modeling in both EV and extended range operation, using a simulation tool developed by GMR&D. Several systems were then selected for intensive study and comparison with two benchmark systems from other OEMs.

The powerflow concept selected as the end result of this study contained several features that were especially well-suited to electric vehicle propulsion:

- The planetary gear ratios required for efficient operation with engine on also resulted in gear ratios that were suitable for electric motor traction drives, with similar speed ratios between the two motors and the transmission output.
- The powerflow was capable of operating at high vehicle speeds both as an EV and with engine on.

One of the key decisions for the final design of the second-generation Volt propulsion system was to split its EV propulsion between two motor-generators, hereafter referred to as motors A and B. Such a split allows engine starting for extended-range driving using torque from an electronically-controlled motor, which makes the starts smoother, quieter, and more efficient than using a slipping clutch or a conventional starter. The split also helps to eliminate the mass of hardware that is not useful for EV driving. Finally, the use of two motors also allows for multiple EV driving modes to increase efficiency, a concept introduced in the first-generation Volt to increase EV driving range under typical long-range driving conditions of moderate to high speeds and low loads. The GEN 2 Volt splits motor power between motors A and B, allowing instant delivery of power from both motors when needed.

Figure 3 shows the selected GEN 2 Voltec powerflow in schematic lever diagram form showing the configuration when operating with engine on. Figure 4 is a simplified lever diagram showing the configuration when operated as an EV.

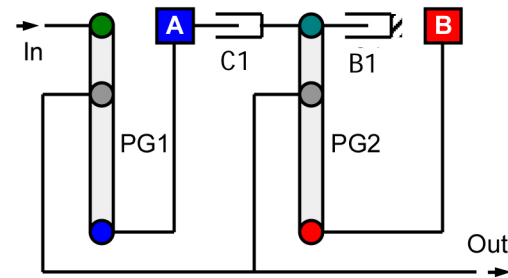


Figure 3. GEN 2 Voltec Drive Unit Powerflow Lever Diagram

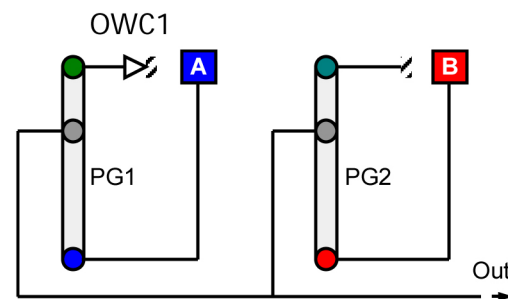


Figure 4. Simplified Lever Diagram, EV Modes

Table 2. Modes of Operation and Clutch States

Operating Mode	B1	C1	OWC1
One Motor EV	Closed	Open	Unloaded
Two Motor EV	Closed	Open	Engaged
Low Extended Range	Closed	Open	Freewheeling
Fixed Ratio Extended Range	Closed	Closed	Freewheeling
High Extended Range	Open	Closed	Freewheeling

In the second-generation Volt, each of the two propulsion motor-generators is geared to a common main transmission shaft using an individual planetary gear set, as shown in the schematic lever diagram. Each motor-generator is connected with a sun gear, and a clutching device can provide reaction torque by holding the ring gear of that planetary gear set. When both of these clutching devices are active as in Figure 4, the two motor-generators are connected in parallel through similar planetary gear sets and a single common final drive and differential to drive the front wheels of the Volt. The second-generation Volt has a two-motor EV mode in which the task of providing peak torque at low speed for crisp launch feel is split between its two motors, and nearly every part of the drive unit is in use to provide maximum output torque and EV acceleration. This

powerflow also enables a distinct, one-motor EV mode of operation to reduce losses under conditions of relatively low torque, such as cruising on a street or highway.

The various modes of operation and corresponding clutch states are summarized in Table 2. During EV operation, the Voltec transaxle utilizes either of two modes:

- One Motor EV - At light loads, the vehicle is propelled using motor B only.
- Two Motor EV - When more drive torque is needed, both motor A and motor B are used to propel the vehicle.

During extended-range operation after the grid energy stored in the battery has depleted, the Volt operates with engine power under the following 3 modes:

- Low Extended Range - Efficient operation at high tractive efforts or low vehicle speeds.
- Fixed Ratio Extended Range - Very efficient operation during typical driving conditions when the vehicle is accelerating, and also allows efficient charging of the battery pack under light vehicle load conditions.
- High Extended Range - Efficient operation at higher speeds for highway cruising.

Voltec Drive Unit

An important consequence of selecting a configuration that allowed motor A and B power to be combined for propulsion was to reduce the total torque and power requirements for the motors. This enabled a reduction in overall motor volume and also allowed bearing size to be substantially reduced. The GEN 2 drive unit integrates the power inverter with the transaxle, providing a significant reduction in volume through elimination of the 3-phase high voltage cables. Volume of the power inverter was reduced from 13.1L to 10.4L.

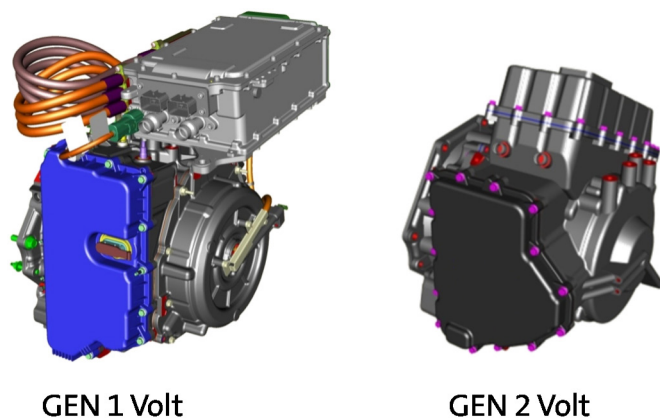


Figure 5. GEN 1 and GEN 2 Drive Unit and Power Inverter

Transaxle

The drive unit resembles a conventional front-wheel drive transaxle in location and form. Figure 6 shows a cross section of the drive unit. On top it has an angled rectangular housing receiving high voltage direct current (DC) cables connected to the battery pack and

containing the power inverter that converts DC current to the high-voltage, variable-frequency alternating current (AC) used by the two propulsion motors and the oil pump motor.



Figure 6. Voltec Drive Unit Cross-section

The three clutching elements C1, B1, and OWC1 (shown in figures 3 and 4) are implemented respectively as hydraulically actuated plate clutch and brake, and mechanical diode.

One area of design emphasis was to minimize the hydraulic power required for transmission operation. The hydraulic system serves three functions: Clutch/brake actuation, lubrication, and motor cooling, with the total hydraulic power determined by flow and pressure demand for these functions at the given operating condition. During design of the transmission, extensive work was done to optimize the clutches and hydraulic circuits, to balance these requirements and reduce the overall hydraulic power. In addition, the oil pump and motor were sized to accommodate the full temperature range of operation, eliminating the need for an engine driven pump.

Propulsion Electric Motors and Inverter

An important goal of the drive unit design was to enable reduction in motor size. Several design features contributed to this goal, in addition to the ability to split A and B propulsion power enabled by the GEN 2 Voltec powerflow described earlier. To reduce the torque requirements and size of the motors, the planetary and transfer gear ratios were selected to provide an increased overall ratio in electric drive mode. Smaller bearings and reduced rotor diameter allowed maximum motor speed to be increased from 9500 rpm to 11000 rpm.

As a result of these enablers, GEN 2 system motor volume was reduced by 20% vs. GEN 1 and motor mass was reduced by 40%. For improved efficiency and cooling capability, both motors are