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ABSTRACT

Building on the experience of the Chevrolet Spark EV battery electric vehicle, General Motors (GM) has developed a propulsion system with increased capability for its next generation Chevrolet Bolt EV. It propels a new larger electric vehicle with significantly greater electric driving range. Through extensive analysis the primary propulsion system components, which include the drive unit, traction electric motor, power electronics, energy storage, and on-board charging module, were optimized individually and as an integrated system to deliver improvements in propulsion system energy, power, torque and efficiency. The results deliver outstanding EV range and fun-to-drive acceleration performance.

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INTRODUCTION

Battery electric vehicles (BEVs) have made sporadic inroads into the light-duty vehicle market since the start of the automotive industry over a century ago. Within the last five years, a new generation of BEVs has emerged, offering useful range for most commuters and a smooth and responsive driving character.

The Chevrolet Spark EV [1, 2], introduced in the US, Canada and Korea in 2014, is an excellent example of that generation. With an EPA label range of 82 miles, 0-60 mph acceleration under 7.5 seconds, and the ability to charge from a 50 kW DC station, the Spark EV is an affordable and fun-to-drive second car with exceptionally low operating cost and no tailpipe emissions.

To bring BEVs to a wider audience of mainstream customers, the Chevrolet Bolt EV must virtually eliminate "range anxiety" by greatly increasing driving range, while building on the strong performance of the previous generation. Key to achieving that goal is a propulsion system that can combine high levels of stored energy, efficiency, power and torque. This paper describes how the propulsion system for the Chevrolet Bolt EV was defined, starting from a challenging set of requirements that included enabling a 200 mile range, comparing design alternatives, and optimizing it through rigorous analysis.

KEY REQUIREMENTS

The key requirements of the propulsion system for the Chevrolet Bolt EV were to significantly increase driving range and to maintain or exceed the excellent acceleration performance of the Chevrolet Spark

EV, when applied to a larger vehicle platform. Table 1 presents some of the main vehicle requirements of the Chevrolet Bolt EV at nominal conditions.

As seen in Table 1, the Chevrolet Bolt EV was targeted to be larger than the Chevrolet Spark EV, yet with improved performance, grade launch capability and, most importantly, driving range, exceeding a US Environmental Protection Agency (EPA) rating of 200 miles. The 200 mile target was developed based on the real customer driving data analysis of the Chevrolet Spark EV and the General Motors range-extended electric vehicle, Chevrolet Volt. That data suggested that a BEV with 200 miles of range could almost completely eliminate "range anxiety" for the vast majority of customers in daily driving situations.

Table 1. Vehicle Performance Requirements

| | Units | Chevrolet Spark EV | Chevrolet Bolt EV |
|------------------|-------|--------------------|-------------------|
| Vehicle Class | | A | B |
| Curb Mass | Kg | 1342 | 1625 |
| 0 – 60 mph | Sec | 7.5 | Under 7 |
| 0 – 30 mph | Sec | 3.1 | 2.9 |
| Max launch grade | % | 28 | 30 |
| EPA Label Range | Miles | 82 | 200+ |

The performance of the vehicle is also dependent on the ambient temperature and the battery energy level. Since the battery is optimized to support a large capacity, it is designed to use a large voltage range. As the remaining battery energy decreases, the battery

voltage decreases, which causes the power capabilities of both the battery and the motor to decrease. In addition to the nominal condition, performance requirements were defined to include this power diminishing effect and targeted to offer excellent driving experience for the customer even when the remaining battery energy was low. Figure 1 presents the acceleration requirement over the traveled distance.

To meet these key vehicle requirements the propulsion system had to be lightweight, compact, quiet, and robust to different driving conditions, including hill climbing, high-speed passing, extended freeway driving and operation in hot and cold temperature extremes.

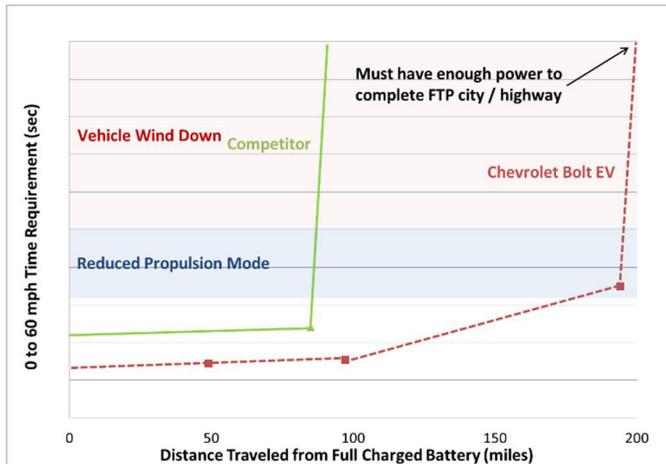


Figure 1. Vehicle Performance Requirement over Driving Range

SYSTEM DESIGN

The first task in the system design was to convert vehicle requirements into propulsion system requirements. The greatly improved driving range depended on high overall system efficiency together with a large increase in battery energy capacity, but the increased battery capacity led to a larger and heavier battery pack. This and the larger targeted vehicle platform in turn led to an increase in total vehicle mass. To maintain or exceed acceleration performance therefore required a propulsion system with higher maximum torque and power capability than that of the Chevrolet Spark EV.

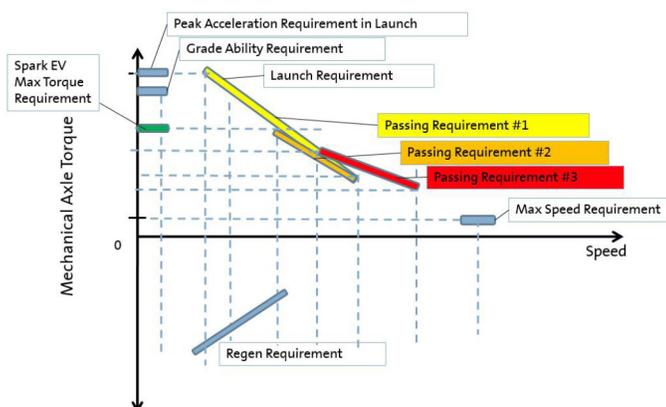


Figure 2. Drive Unit Axle Torque Requirements

Figure 2 shows the critical performance requirements and the corresponding torque/power required at the driven axle. Different performance targets (Vehicle launch, grade-ability, passing, regenerative braking, etc.) set torque requirements at different speeds. When combined, they became the torque envelop requirement. To achieve this level of axle torque and power, various combinations of inverter/motor pairs, associated drive unit designs, and gear ratios were considered.

Figure 2 also illustrates that the max torque requirement was greatly increased from that of the Chevrolet Spark EV. A higher motor to wheel ratio was necessary to deliver that higher peak torque. Since the Chevrolet Spark EV’s planetary gear design was not able to achieve this high motor torque multiplication, alternative gear architectures were evaluated. In the end, an offset gear arrangement offered the best balance between performance and efficiency for the Chevrolet Bolt EV.

A Design for Six Sigma (DFSS) optimization process [3] was followed which considered several major design control factors as inputs. Key vehicle performance metrics, EV range, and grade launch capability were selected as responses to be measured. The battery temperature, energy variation effects and vehicle mass were considered as noise parameters in this design process (see Figure 3).

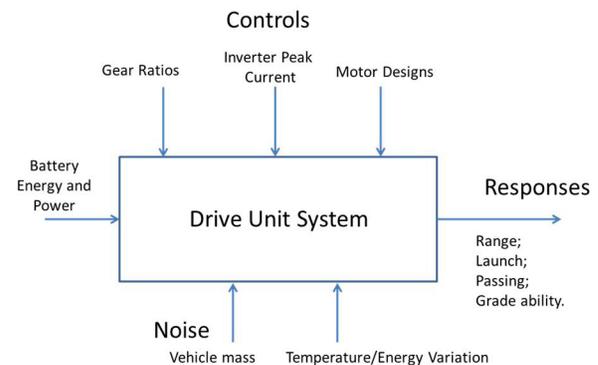


Figure 3. Design Optimization Setup

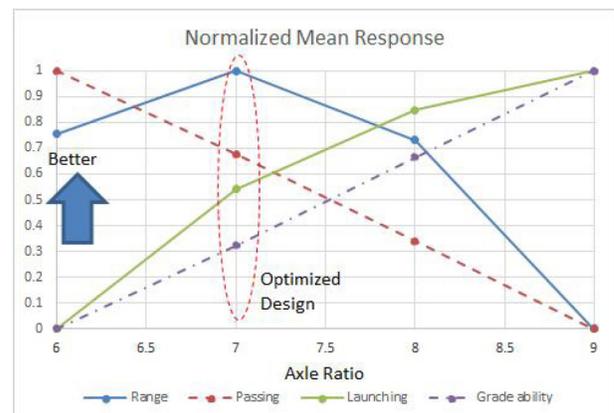


Figure 4. Axle Ratio Response Results in Design Optimization Process

The DFSS process was used to rigorously evaluate the design tradeoffs and achieve the optimal solution. For example, the analysis determined that, as gear ratio increased, launch acceleration and maximum grade capability improved (more torque) but high speed passing performance decreased. Ultimately, the gear ratio that offered the best balance between EV range (system efficiency) and overall vehicle performance was selected (see Figure 4). The selected design was determined to be the most robust for meeting all requirements over a wide temperature range and different vehicle masses. The DFSS process was used iteratively in combination with optimization for cost and packaging, performed in parallel. These factors often brought new constraints into the design process and a new tradeoff was required that resulted in further fine adjustments to the system design.

After all these factors were considered and thousands of simulation analyses were evaluated, the final architecture of the propulsion system was selected for the Chevrolet Bolt EV. As seen in Figure 5, the end result was that the propulsion system of the Chevrolet Bolt EV provides a much improved axle torque and power capability across the entire axle speed range compared to that of the Chevrolet Spark EV.

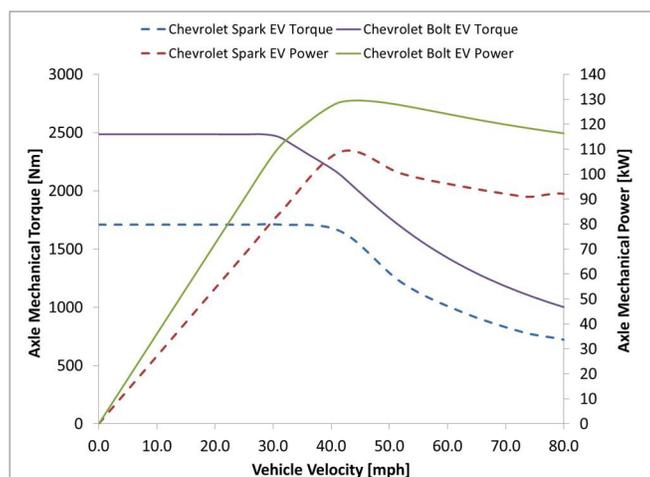


Figure 5. Axle Torque and Power Comparison between the Chevrolet Spark EV and the Chevrolet Bolt EV

The greatly increased EV range capability and performance improvement of the overall propulsion system rely not only on an optimized system design but also on improvements in each component of the propulsion system. In the following sections design improvements are explained for the battery, drive unit, electric motor, and power electronics.

BATTERY

One of the key components for the Chevrolet Bolt EV propulsion system is the rechargeable energy storage system (RESS), commonly known as the battery pack. It provides a high voltage (HV) source of propulsion power and energy. The battery pack had to balance the need for high energy, power, and efficiency in a compact, lightweight package.

Table 2. Design Optimization Strategy and Enablers

| |
|---|
| Packaging/Space Utilization Optimization |
| Cell and Bi-cell Format Optimization |
| Power and Energy Ratio Optimization |
| Chemistry Selection |
| Active Cooling and Heating Optimization |
| Safety and Crash Regulation Requirement with Optimized Topology |

To ensure a robust, well-balanced design capable of meeting these requirements, the process demanded an execution of design optimization strategies and enablers. (As shown in Table 2).

The optimization steps were:

1. **Packaging/Space Utilization Optimization:** The goal of the RESS internal design was to maximize usage of its internal space without compromising the integrity and robustness of the overall system. A distributed electrical system approach was used to balance the package space utilization between under body and under hood locations. Components (e.g., RESS heater, etc.) which are normally integrated into the battery pack were packaged to the under hood location to maximize the amount of space for battery cells. From the layout standpoint, the pack has five sections in total. A DC bus bar assembly is installed from each section to another and is looping through the entire pack to create HV circuit. A manual service disconnect (MSD) is placed to have RESS ability to disconnect from the propulsion system before the service. A battery disconnect unit (BDU) is used to control relays, fusing and current sensing function. It has the ability to activate the HV bus by bringing the HV Battery online in a safe, quiet manner while providing isolation to chassis during all possible vehicle conditions. BDU also provides HV accessory load fusing and HV Battery Pack current sensing for state of charge and health monitoring.
2. **Cell and Bi-cell Format Optimization:** The cell and bi-cell design configuration was critical to the pack module's desired amount of power and energy. With a fixed amount of pack space available, it was essential to have the right number of modules/cells/bi-cells and to confirm that the required amount of power and energy could be achieved simultaneously. There are total 288 cells in the pack. The pack consists of 5 sections in total and each section has two modules. The amount of cells are evenly distributed within each of two modules. There are 96 cell groups in total and 3 cells per group.
3. **Chemistry Selection:** Selecting the right cell chemistry for EV batteries has a significant impact on both cost and performance. The amount of power and energy required for different vehicle applications is directly linked to the chemistry of the battery cell. These fundamental characteristics were carefully examined from both material science and engineering design perspectives. The potential and limitations of various cell components (e.g. positive electrodes, negative electrodes,

different classes of electrolytes) were studied to produce the best match to performance and range requirements.

Specifically, the ideal choice was a lithium-based chemistry, which provided thermal resistance, was environmentally friendly, charged rapidly, and delivered a long useful life. The nickel-rich Li-ion chemistry provides improved thermal performance over other chemistry, which required smaller active cooling system for more efficiency packaging.

4. Active Cooling and Heating Optimization: The pack's temperature directly influences its performance and life expectancy. Analysis of six different concepts was performed to predict RESS cooling/heating performance as well as the effectiveness of heat transfer during warm up events to ensure that the best solution was chosen to maximize EV range while maintain the best performance in both hot and cold conditions. An active thermal liquid cooled system, like Chevrolet Volt [4], is placed for circulating coolant through each module and each section of the pack. A cooling fin is built in between cells and each fin is connected to the cooling plate so the heat generated from cell can be transferred out to the cooling plate which has coolant flows through to perform the heat exchanges. The coolant flow path of the pack is studied and optimized to ensure delta pressure drop is within the cooling system and pump capability.
5. Safety and Crash Regulation Requirement with optimized topology: Safety was the overriding priority. All design concepts were carefully evaluated to ensure that Federal Motor Vehicle Safety Standard regulations and GM rigorous internal crash design requirements were met and best practices followed.

From a system design standpoint, the matrix of desired battery pack characteristics was placed through system design simulations for analysis. This matrix contained the pack performance curves, such as those for state of charge, DC current, DC voltage, and temperature. Furthermore, both beginning of life (BOL) and end of life (EOL) performance were carefully studied to ensure that target life and durability requirements were met. Thus, after numerous iterations of design optimization, the Lithium Ion battery pack design shown in Figure 6 was chosen.

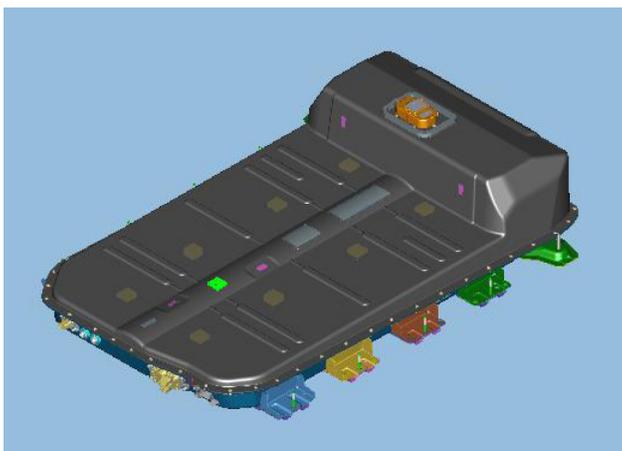


Figure 6. The Chevrolet Bolt EV Battery

The RESS comparison of the Chevrolet Spark EV and the Chevrolet Bolt EV is shown in Table 3.

Table 3. Battery Comparison between the Chevrolet Spark EV and the Chevrolet Bolt EV

| Vehicle Name | Chevrolet Spark EV | Chevrolet Bolt EV |
|---|-------------------------------|-------------------------------|
| Range (EPA) | 82 Miles | >200 Miles(est.) |
| Battery Chemistry | Lithium Ion | Lithium Ion (Nickel-rich) |
| Battery Nominal Energy | 20 kWhr | 60 kWhr |
| Battery Mass | 260 kg | 436 kg |
| Max Battery Power | 120 kW | 150 kW |
| Battery Nominal Voltage | 360V | 350V |
| Battery Position | Underfloor | Underfloor |
| Battery Cooling System | Liquid active thermal control | Liquid active thermal control |
| Manual Service Disconnect Access Position | Interior | Interior |

DRIVE UNIT

The Drive Unit (DU) of the Chevrolet Bolt EV was designed to optimize package space, noise, mass, manufacturability, application flexibility, cost and efficiency. It provides several functions including electric motor traction, motor end cover, motor cooling, lubrication system, sumps for cooling and lubrication, gear reduction, differential split to outputs, park system, electric mode switch (PRNDL), 12V pump, filter and accessory support, in a maintenance-free design. Figure 7 shows a labeled cross section showing the major DU components and outlines how all the internal and external components are integrated.

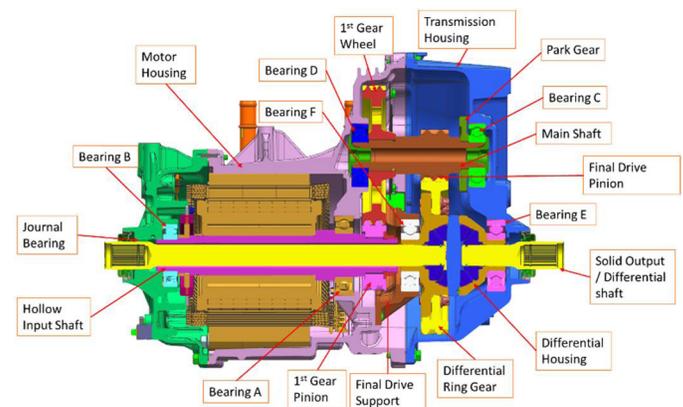


Figure 7. The Chevrolet Bolt EV Drive Unit

Gear Scheme, Structure, and Packaging

The DU was packaged around the axle to minimize impact to vehicle front compartment volume. Total DU height and length were minimized by reducing the motor diameter and designing the housing and gear system layout to maintain necessary ground clearance. The compact DU design allowed it to be located in the exact centerline of the vehicle, which resulted in identical length left and right axle shafts. This design reduces integration cost, increases manufacturing efficiency and minimizes torque steer.

With a single speed gear set power flow architecture the DU provides advantages in the park system loading. The split lines, one between end cover and motor housing and the other between motor housing and gearbox housing, provide a high structural stiffness and enable the motor assembly to be manufactured as a separate stand-alone unit. This approach also allows motor compartment maintenance without disassembling the whole DU.

Lube and Cooling

A variable speed 12 volt electric oil pump provides the flexibility to minimize the propulsion energy consumption when driving while delivering full lubrication and cooling under difficult duty cycles, such as steep grade motor cooling conditions where splash lube designs would be challenged and high speed conditions where gear tooth pitch line velocity would be challenged. Also, a variable-speed 12V oil pump and optimized filter position minimized ATF volume inside the DU, which helped to reduce cost, mass and spin losses.

The DU uses full synthetic DEXRON VI transmission fluid to improve efficiency by lowering mechanical oil drag losses. The DU is cooled by the vehicle cooling system, using the coolant sump on the bottom side of the DU to maximize surface contact with fluid inside of the DU. This avoided the need for a dedicated oil cooling loop, reducing cost, mass and design complexity.

Efficiency and NVH

A fixed single-speed gear set in combination with optimized oil volume to reduce spin loss increased power flow efficiency. Also contributing to low DU spin losses are design elements such as using a layout that keeps counter gears away from oil, adding a baffle to further isolate gears from oil and keeping oil out of the motor air gap. Specially developed ball bearing with optimized efficiency performance for this high torque fixed ratio gear set and controlled oil flow for bearing lubrication gave further improvements. Controlled lubricant flow between the motor and gear system compartments through specifically designed orifices contributes to low total oil volume which minimize spin loss in the differential gear set (see [Figure 8](#)).

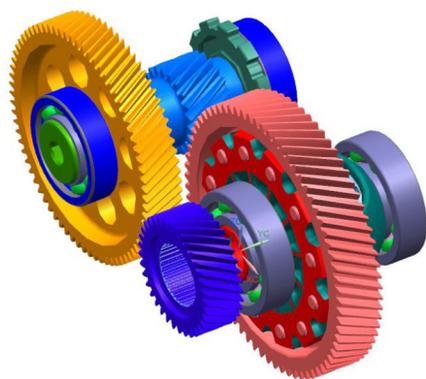


Figure 8. The Chevrolet Bolt EV Drive Unit Gear Set

BEVs are inherently sensitive to noise and vibration due to the lack of combustion engine masking noise. To minimize audible noise, the DU was optimized for stator-to-housing clearance, gear tooth micro geometry, structural housing design and stiffness, mount bracket design and pump operating schedule.

Some of the key parameters of the Chevrolet Bolt EV DU are compared with the DU of the Chevrolet Spark EV in [Table 4](#).

Table 4. Drive Unit Comparison between the Chevrolet Spark EV and the Chevrolet Bolt EV

| | Chevrolet Spark EV | Chevrolet Bolt EV |
|-----------------------|--------------------|-------------------|
| Peak Axle Torque (Nm) | 1710 | 2500 |
| Gear ratio | 3.87 | 7.05 |
| Mass (kg) | 68 | 76 |
| Oil Type | DEXRON VI | DEXRON VI |
| Total ATF Volume (L) | 4.2 | 2.9 |

ELECTRIC MOTOR

A permanent magnet (PM) motor was used in the propulsion system of the Chevrolet Bolt EV [5], for inherent properties of higher efficiency and less vibration. [Figure 9](#) shows the critical torque-speed points, at different operating regions of the combined drive cycle for which the motor design was optimized. Different motor configurations, e.g. number of stator turns, stack lengths etc. were studied and analyzed to achieve the required performance, focusing especially on the higher power needed in the mid to high speed range. Parameters like magnet lengths, widths and angles, and stator slot opening dimensions, were varied in tens of thousands of finite element design cases to maximize efficiency at the key operating points while meeting the requirements for low noise and vibration.

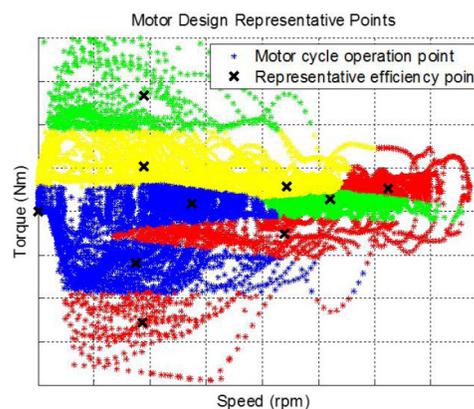


Figure 9. Critical Efficiency Operating Points for Motor Design

Magnets were buried inside the rotor in a two layer 'V' arrangement ([Figure 10](#)). A double-layer arrangement of magnets and barriers offers design-flexibility and enhances rotor saliency that results in improved motor performance, especially power at higher speed.

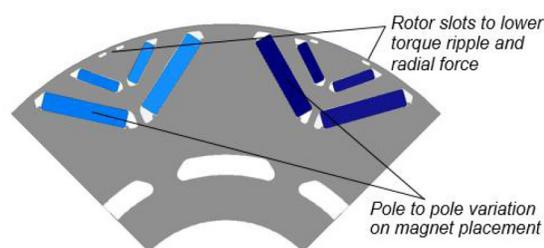


Figure 10. Slice of Double Barrier Rotor

The magnet material selected was Neodymium Iron Boron and its placement in the rotor features an asymmetry between adjacent poles, so that torque ripple and radial force are minimized. Asymmetric placement of an additional pair of small slots stamped near the rotor outer surface under each pole was also optimized for the same purpose.

A bar wound stator (Figure 11) construction known to provide high slot fill, improved thermal performance and higher efficiency was also implemented in the electric motor. However, in order to lower the winding AC effects and copper losses at higher speeds, the motor used smaller conductors in the slot by using six conductors per slot, instead of the four conductors per slot design as used in the Chevrolet Spark EV motor. To meet the stringent requirements for low noise and vibration, stator tooth tips were also optimized [5]. This technique, in addition to the ones described above for the rotor, avoided the need for rotor skew, which is known to lower machine performance.

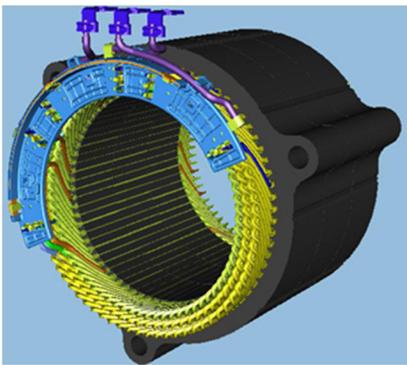


Figure 11. The Chevrolet Bolt EV Stator

Comparison of the key parameters of the Chevrolet Bolt EV electric motor with that of the Chevrolet Spark EV are shown in Table 5 below.

Table 5. Electric Motor Parameters between the Chevrolet Spark EV and Chevrolet Bolt EV

| | Chevrolet Spark EV | Chevrolet Bolt EV |
|--|--------------------|-------------------|
| Peak Power density (W/cm ³) | 18.5 | 28.8 |
| Peak Torque density (Nm/ cm ³) | 0.09 | 0.07 |
| Peak Torque (Nm) | 540 | 360 |
| Max speed (rpm) | 4500 | 8810 |
| Rated current (Arms) | 450 | 400 |
| Nominal DC bus voltage (V) | 350 | 350 |
| Motor stack length (mm) | 125 | 125 |
| Motor outer diameter (mm) | 213 | 204 |
| Number of poles | 8 | 8 |

POWER ELECTRONICS

Figure 12 shows the Chevrolet Bolt EV high voltage DC bus mechanization diagram with the Single Power Inverter Module (SPIM), Air Conditioner Compressor Module (ACCM) and Cabin Heater and Cooler Module (CHCM) connected to the RESS through

a High Power Distribution Module (HPDM). The battery heater and On-Board Charger Module (OBCM) were daisy chained with the Accessory Power Module (APM), which was also connected through the HPDM via another separate connection from the RESS.

The high voltage DC bus mechanization selected here ensured stability and controllability of the system, avoiding any unwanted oscillations or electrical resonances [6]. It also satisfied the need for minimizing sequence complexity and duplicate need for low voltage bias power during charging or motoring operation.

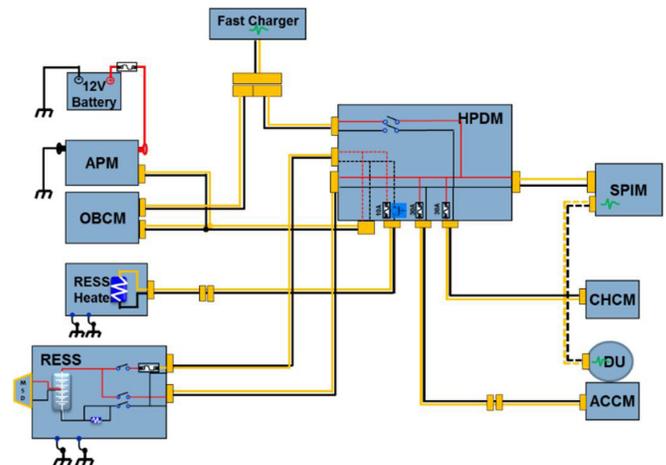
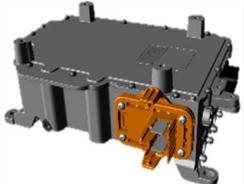


Figure 12. HV DC Bus Mechanization Diagram

Major requirements and design improvements between the Chevrolet Spark EV SPIM and the Chevrolet Bolt EV SPIM (both of them are liquid cooled) are described in Table 6. The electric drive system design is capable of delivering 9% more maximum power with a 7% decreased in maximum AC phase current. Another significant capability improvement is in continuous AC and DC current area in the range of 22~27%.

Table 6. SPIM Comparison between the Chevrolet Spark EV and the Chevrolet Bolt EV SPIM Parameter Chevrolet Spark EV SPIM Chevrolet Bolt EV SPIM

| | Chevrolet Spark EV SPIM | Chevrolet Bolt EV SPIM |
|----------------|---|---|
| SPIM Parameter |  |  |
| Size/ Weight | 13.1 Liter/13.6 Kg | 7.8 Liter/9.6 Kg |
| AC Current | Peak= 430 Arms Continuous = 150 Arms | Peak = 400 Arms Continuous = 184 Arms |
| Maximum Power | 140 kVA | 153 kVA |
| DC Current | Peak = 410 Amp Continuous = 135 Amp | Peak = 450 Amp Continuous = 172 Amp |
| Power Density | 84% Improved (kVA/ Liter) | |
| Power Density | 55% Improved (kVA/ Kg) | |

Two of the major power stage components that contribute to achieving the improvements in the SPIM described above are the power module and the DC bulk capacitor [7]. Table 7 compares specifications for the SPIM of the Chevrolet Spark EV and the Chevrolet Bolt EV.

Table 7. Power Module and DC Bulk Capacitor Comparison between the Chevrolet Spark EV and the Chevrolet Bolt EV

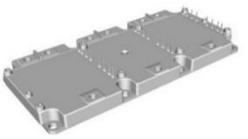
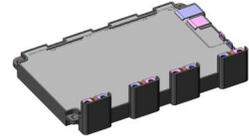
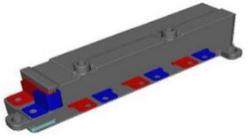
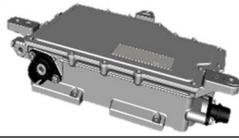
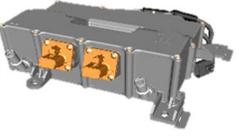
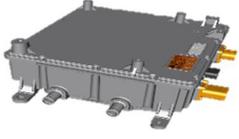
| | Chevrolet Spark EV SPIM | Chevrolet Bolt EV SPIM |
|--------------------|---|---|
| Power Module |  |  |
| Silicon (per IGBT) | 7% Increased area per IGBT switch | |
| DC Bulk Capacitor |  |  |
| Capacitance (EOL) | 29% Decreased total capacitance needed | |

Table 8. HV Power Electronics Components Comparison between the Chevrolet Spark EV and the Chevrolet Bolt EV

| | Chevrolet Spark EV HV Components | Chevrolet Bolt EV HV Components |
|--------------------------------|---|---|
| APM (Accessory Power Module) |  |  |
| | 5.2 Liter/ 5.2 Kg | 2.8 Liter/ 3.2 Kg |
| | 2.2 kW | 1.6 kW |
| OBCM (On-Board Charger Module) |  |  |
| | 13.0 Liter/ 9.3 Kg | 12.3 Liter/ 12.0 Kg |
| | 3.3 kW | 7.2 kW |

As shown in Figure 12 other HV components are the 1.6 kW APM, the 7.2 kW OBCM and the HPDM. The HPDM works as a junction box to connect HV components and an external off-board DC fast charger. This vehicle is capable of both on-board and off-board charging and that's why in addition to a 7.2 kW OBCM there is also

an optional 50 kW Direct Current (DC) off-board fast charge system that can complete a full charge (0 - 80% usable range) in approximately 20 minutes. A vehicle outfitted with the SAE combo receptacle has the same AC interface used for onboard charging and additional DC pins to transfer the DC energy directly from a fast charge station. Table 8 shows a comparison of the APM and OBCM between those in the Chevrolet Spark EV and the Chevrolet Bolt EV.

SUMMARY

The propulsion system for the Chevrolet Bolt EV builds on the strengths and lessons from the previous generation Chevrolet Spark EV propulsion system. Through careful analysis and balancing of key attributes and close attention to efficiency in every component, this new propulsion system enables the Chevrolet Bolt EV to deliver over 200 miles of range together with outstanding acceleration in a new, larger vehicle.

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DEFINITIONS/ABBREVIATIONS

AC - Alternating Current

ACCM - Air Conditioner Control Module

APM - Accessory Power Module

ATF - Automatic Transmission Fluid

BEV - Battery Electric Vehicle

BOL - Beginning of life

CHCM - Cabin Heating Control Module

DC - Direct Current

DFSS - Design for Six Sigma

DU - Drive Unit

EPA - Environmental Protection Agency

EV - Electric Vehicle

EOL - End of life

GM - General Motors

HPDM - High Power Distribution Module

HV - High Voltage

MSD - Manual Service Disconnect

PM - Permanent Magnet

RESS - Rechargeable Energy Storage System

SPIM - Single Power Inverter Module

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