

Electric Motor Design of General Motors' Chevrolet Bolt Electric Vehicle

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ABSTRACT

A permanent magnet synchronous motor (PMSM) motor is used to design the propulsion system of GM's Chevrolet Bolt battery electric vehicle (BEV). Magnets are buried inside the rotor in two layer 'V' arrangement. The Chevrolet Bolt BEV electric machine rotor design optimizes the magnet placement between the adjacent poles asymmetrically to lower torque ripple and radial force. Similar to Chevrolet Spark BEV electric motor, a pair of small slots are stamped in each rotor pole near the rotor outer surface to lower torque ripple and radial force. Rotor design optimizes the placement of these slots at different locations in adjacent poles providing further reduction in torque ripple and radial force. As a result of all these design features, the Chevrolet Bolt BEV electric motor is able to meet the GM stringent noise and vibration requirements without implementing rotor skew, which (rotor skew) lowers motor performance and adds complexity to the rotor manufacturing and hence is undesirable.

A bar-wound stator construction, similar to Chevrolet Spark battery electric vehicle, is implemented in Chevrolet Bolt BEV. Bar-wound construction, which GM has adopted for most of its electric and hybrid vehicle motor construction, is known to provide high slot fill, short end-turn length, improved thermal performance, and improved vehicle efficiency especially at low to medium speed ranges. System design, including gearing takes advantage of these machines to ensure the aggregate majority of the driving energy is consumed in the higher efficiency areas of the motor efficiency envelope. However in order to lower the winding ac effect at higher speeds and expanded the high efficiency portions of the envelope, the Chevrolet Bolt BEV motor implements six conductors per slot design while four conductors per slot design was used in Chevrolet Spark motor design. As a result, individual conductor size is smaller in new design resulting in reduced winding AC effects and improved joule loss at high speed operations. Winding layout design in Chevrolet Bolt BEV motor is optimized to minimize voltage between conductors within the slot. This has allowed to eliminate the slot insulation between conductors, further increasing the slot fill and reducing material and manufacturing costs. Stator design of Chevrolet Bolt BEV adopts a special feature, introduced in Gen2 Chevrolet Volt, the stator slot opening size and placement under each pole are optimized to lower torque ripple and radial force. This feature supplements the torque ripple and radial force reduction features introduced in the rotor design as described above.

The high performing electric machine is coupled with a high performing control algorithm to deliver maximum system efficiency and performance. A six-step mode of inverter control is implemented to maximize the voltage utilization. As the speed is increased control automatically transitions to six-step mode from space vector PWM (SVPWM) seamlessly. Torque response dynamics at six-step control is reduced, as expected, from SVPWM mode of control. However, the torque control dynamics with six-step control is able to meet the torque response requirements of the vehicle. Control is stable and robust even with very fast vehicle acceleration.

CITATION: Momen, F., Rahman, K., Son, Y., and Savagian, P., "Electric Motor Design of General Motors' Chevrolet Bolt Electric Vehicle," *SAE Int. J. Alt. Power.* 5(2):2016, doi:10.4271/2016-01-1228.

INTRODUCTION

Vehicle regulation worldwide favor vehicles that emits no or low pollutants and CO₂. Curbing vehicle emissions and improving vehicle efficiency to meet these regulatory requirements require multi-prong technical solutions and vehicle electrification technologies enabling Hybrid Electric Vehicles (HEVs), Plug-In Hybrid Electric Vehicles (PHEV), Extended Range Electric Vehicles (EREV), and BEVs are part of that.

GM is developing BEVs as a part of its plan for vehicle electrification that includes EREVs such as Chevrolet Volt, PHEVs such as recently announced Cadillac CT6, and HEVs such as Chevrolet Tahoe, or E-Assist mild hybrid vehicle such as Buick Lacrosse. The GM EV1 BEV introduced in 1996 was the first modern BEV and the Chevrolet Spark BEV, was introduced in the market in 2013. Built upon the knowledge and experience gained from EV1, Spark EV, and Chevrolet Volt, the propulsion system of Chevrolet Bolt BEV offers significant improvement in the BEV electric driving vehicle range as well as in the peak performance.

The battery supplies the required energy to the electric vehicle. However 100 percent all of the battery's energy to drive the vehicle, as well as 100 percent of the vehicle dynamic energy recaptured through effective regenerative braking pass through the electric machine. So a highly efficient electric motor over a wide range of driving conditions is highly desirable.

The electric motor for Chevrolet Bolt BEV has been designed and developed with these objectives in mind. The proven bar wound stator construction, which is the most advantageous for automotive electric motors was selected for GM Chevrolet Bolt BEV motor. To reduce motor size and still meet the overall performance requirements, a larger numerical gear reduction was chosen for Chevrolet Bolt BEV drive unit (DU) compared with Chevrolet Spark BEV DU. So, the new electric motor runs at higher speeds compared to Chevrolet Spark motor. In order to reduce the winding AC effects, a six conductors per slot design is selected for the Chevrolet Bolt BEV motor. Winding layout is optimized to reduce voltage stresses between conductors within each stator slot. As a result, slot-insulation paper is only placed around the slot, but the insulation paper between conductors is eliminated. This has resulted in higher slot-fill and further reduction of joule loss of the motor. Stator slot opening size and placement are optimized, similar to Gen2 Volt motors, to lower torque ripple.

The Chevrolet Bolt BEV motor rotor has two layer V magnet pole design similar to Spark BEV motor. High energy NdFeB type magnets are selected for the motor. Magnet size, barrier shape, and angular placements are optimized between consecutive poles to maximize motor performance and efficiency while minimizing torque ripple and radial forces. Rotor optimization along with stator slot-opening modulation allowed motor design to eliminate rotor skew with acceptable noise behavior resulting in improved motor performance and efficiency.

The efficient electric motor and control combined with the new drive unit makes the Chevrolet Bolt BEV to deliver a spirited, compelling, and smooth electric driving performance. More details about the electric motors and its performances are presented in the subsequent sections.

MOTOR REQUIREMENTS

The key requirements of the Chevrolet Bolt BEV vehicle are to significantly increase driving range, maintain or exceed the class leading performance of the Spark EV, while increase the system bandwidth to be applied to a larger vehicle platform. Compared to the Spark EV, the Chevrolet Bolt EV is targeted to motivate a larger vehicle. However, the acceleration, passing, and grade launch requirements are set same or better than Chevrolet Spark [1]. Most importantly, next generation BEV range target is set to exceed an EPA label rating of 200 miles. The 200 mile target is developed based on the real customer driving data analysis of the Spark EV and the General Motors EREV Volt [2].

In order to meet the acceleration, passing, and range requirement of Chevrolet Bolt BEV significantly higher torque and power (than Chevrolet Spark) are needed at the vehicle axle. Figure 1 shows the critical performance requirements for initial acceleration and vehicle passing [1]. These requirements can be used to develop the overall

torque and power requirements at the vehicle axle. To achieve this level of axle torque and power, a various combinations of inverter/motor pairs, associated drive unit designs, and gear ratios are considered [1].

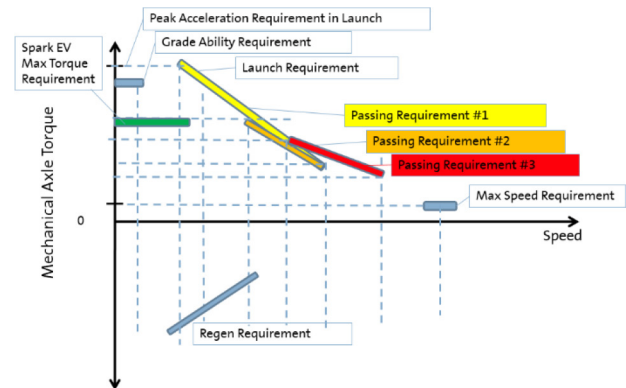


Figure 1. Chevrolet Bolt BEV DU axle torque requirement.

Table I below lists the required motor parameters of the Chevrolet Bolt BEV motor. These requirements are derived based on the DU study mentioned above.

Table I. Chevrolet Bolt BEV Motor Parameters

Torque (Nm)	360
Power (kW)	150
Max Speed (rpm)	8810
Max Motor Current (A)	400

Fig. 2 shows the operating torque-speed points (time series data) of the motor for US06, LA92, NEDC, FTP urban and highway drive cycles. Machine for the Chevrolet Bolt BEV is optimized based on the motor operations in these drive cycles. Critical torque-speed points representing the different operating clusters of the combined drive cycle are shown in figure 3. Motor design is optimized for these key operating points.

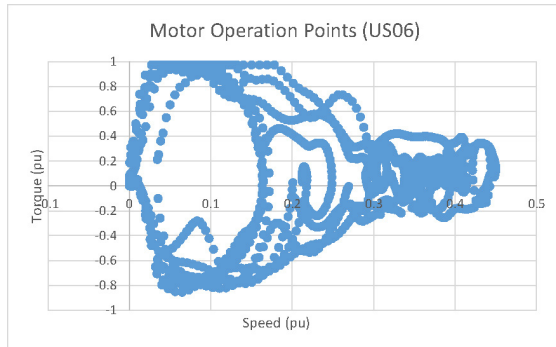
DESIGN OF ELECTRICAL PROPULSION SYSTEMS

The Chevrolet Bolt BEV machine is a PMSM. The rotor is interior permanent magnet (IPM) type where the magnets are buried inside the rotor. The IPM motor has well-known properties such as i) extended constant power range, ii) good overall efficiency, iii) good power factor, which make this motor a favorable candidate for automotive application. Figure 4 shows an exploded view of the motor drive system of the GM Chevrolet Bolt BEV.

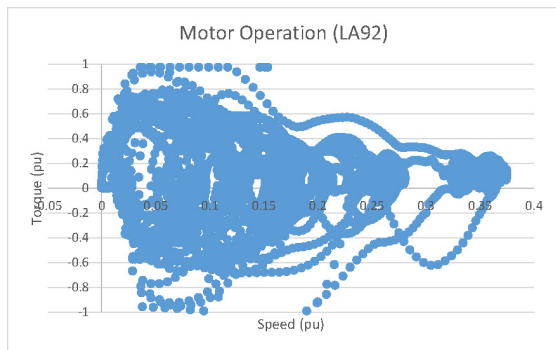
Stator Design

A bar wound stator, similar to GM previous motor designs, is selected for the Chevrolet Bolt BEV electric motor. The bar wound stator construction holds several known advantages over the more conventional stranded design [3, 4]:

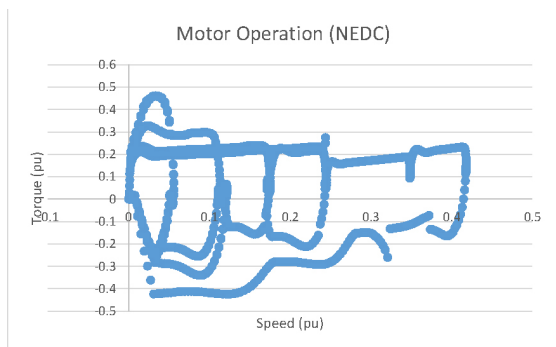
- Higher slot fill
- Shorter end-turn enabling longer active stack length
- Improved thermal performance
- Improved high voltage protection
- Fully automated manufacturing process



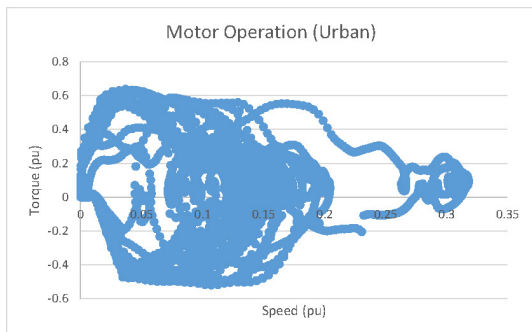
a.



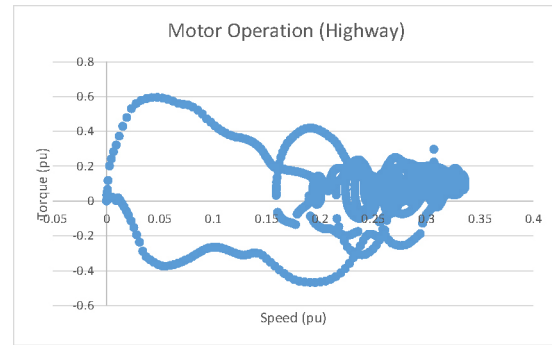
b.



c.



d.



e.

Figure 2. (cont.) Motor operating points for several standard drive cycles.

Bar wound construction uses hair-pin type conductors which are inserted, twisted, and welded to generate wave-pattern of the winding in contrast to a more conventional lap or concentric winding pattern of stranded design. Figure 5 shows the hair-pin, before and after twist.

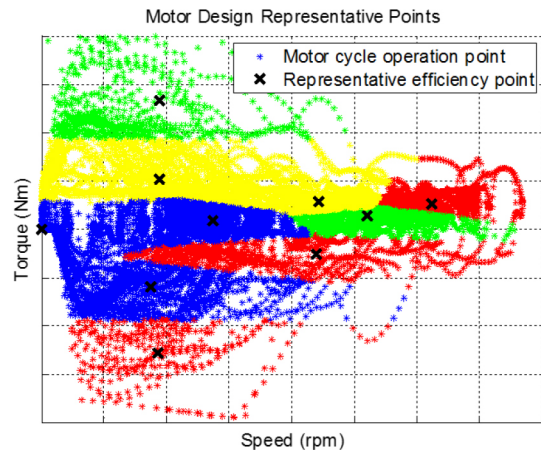


Figure 3. Motor key operating points

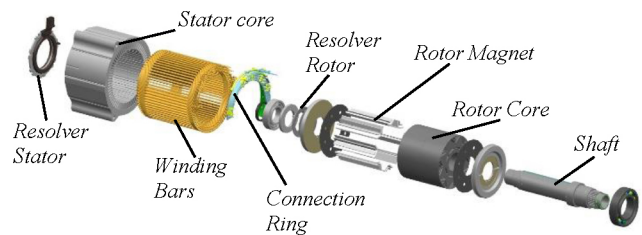


Figure 4. Exploded view of the electric motor



a.

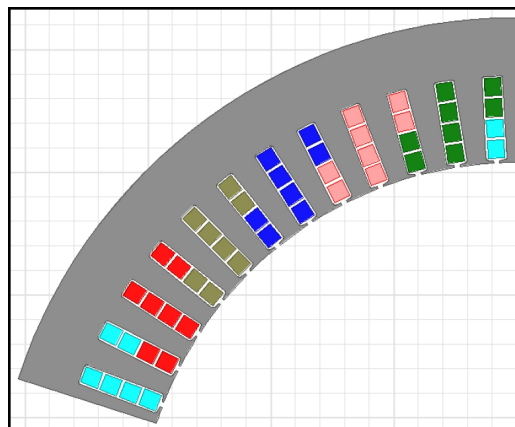
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Figure 5. Hair-pin design before (a) and after (b) twist

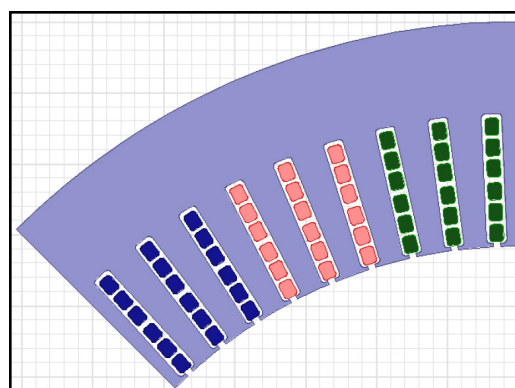
However the well-known issue with the bar wound design, the AC winding effect, can lower motor efficiency at higher speeds. In order to address this for the Chevrolet Bolt BEV, six-conductor per slot is selected instead of four-conductor per slot of the GM previous motor designs. Increasing the number of conductors per slot, reduces conductor size. Figure 6 shows the 6-conductor per slot design of the Chevrolet Bolt BEV motor and compares that with the 4-conductor per slot design of the Chevrolet Spark BEV motor. Reduction of conductor size reduces the winding AC effect resulting in lower joule loss at high speed operations of the motor.

This is illustrated in figure 7 which compares the AC winding effect of a four-conductor per slot design versus a six-conductor per slot design for the same stator lamination of the Chevrolet Bolt BEV motor. The four-conductor per slot design has a relatively higher slot-fill compared to a six-conductor per slot design, resulting in lower dc resistance as evidenced in figure 7. However, the 6-conductor per slot design shows significant improvement over the 4-conductor per slot design at higher speeds.

Figure 8 shows the winding AC effect for the Chevrolet Bolt BEV motor as a function of motor phase current and rotor speed and compares that with the Chevrolet Spark BEV motor winding AC effect. A reduction of AC winding effect of 30% and more is achieved at motor speeds of 4000 rpm and above.



a.



b.

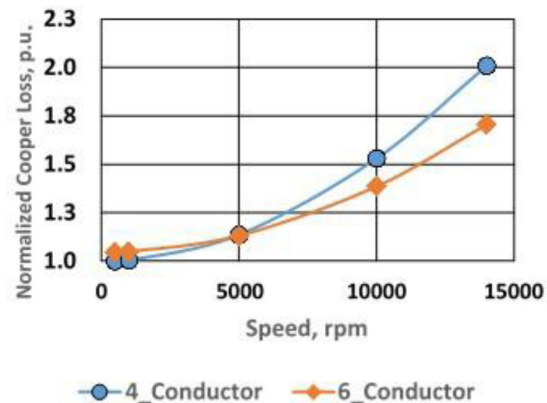
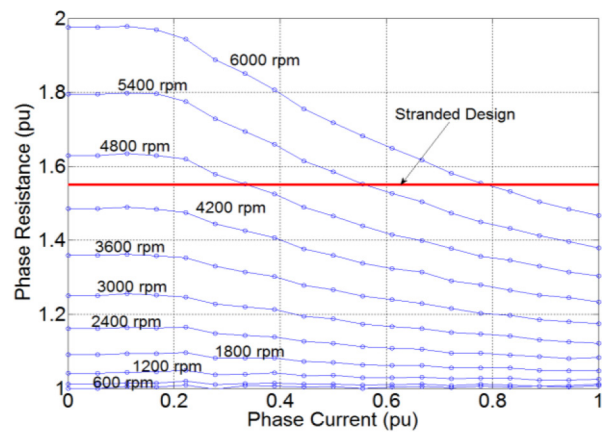
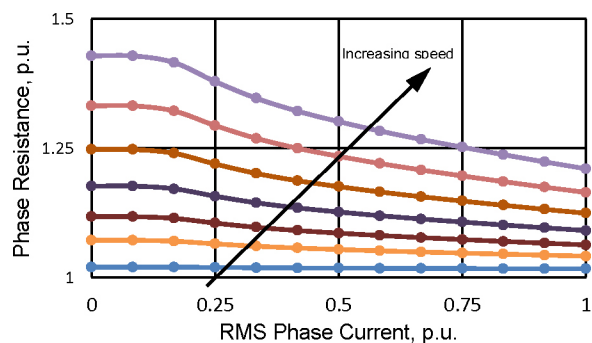


Figure 7. Normalized joule loss of a four-conductor per slot design vs a six-conductor per slot design

In order to improve the slot-fill further, the Chevrolet Bolt BEV stator uses a simple two-piece slot-insulation around the stator slot to protect the windings from shorting to the lamination steel. However, the new design has eliminated the slot-insulation between the conductors. This is illustrated in figure 9 which compares the Chevrolet Spark B-shaped slot-liner with the simplified two-piece slot liner of the new design.



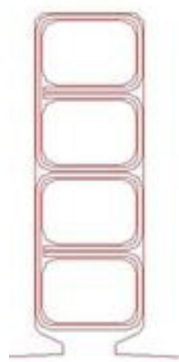
a.



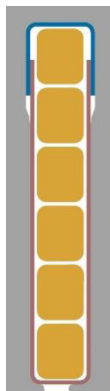
b.

Figure 8. Winding AC effect of Chevrolet Spark BEV motor (a) and Chevrolet Bolt BEV motor (b)

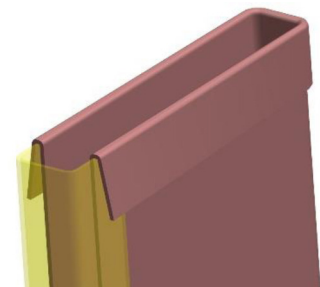
Figure 6. 4-Conductor per slot design of Chevrolet Spark (a) and 6-conductor per slot design of Chevrolet Bolt BEV (b) motors



a.



b.



c.

Figure 8. Chevrolet Spark B-shaped slot-insulation (a) and new two-piece slot-insulation (b and c)

The simple slot-insulation design greatly improves the stator manufacturing process. However, to make room for this two-piece slot insulation which requires an area of overlapping region near the slot-bottom as shown in [figure 8 \(b\) and \(c\)](#), stator lamination is modified near the slot bottom. This is further illustrated in [figure 9](#). This modification did not compromise any of the motor performances, however, simplified the stator slot insulation design significantly.

The elimination of slot-liner between the conductors exposes each conductor within the slot to the relative potential of its neighboring conductor. In order to minimize the voltage potential between the conductors within the slot, the winding layout has been optimized, using GM's own proprietary tool-method.

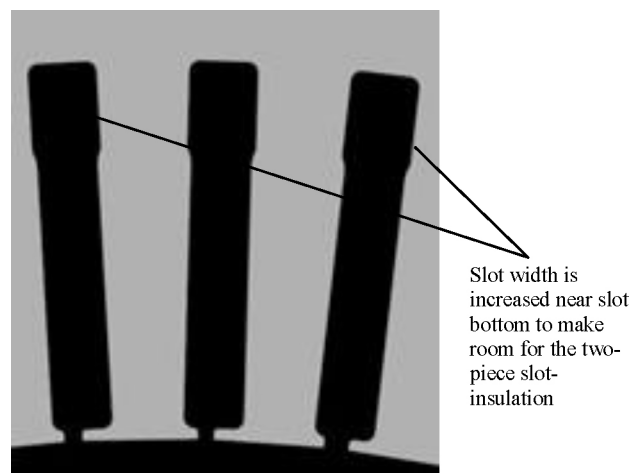
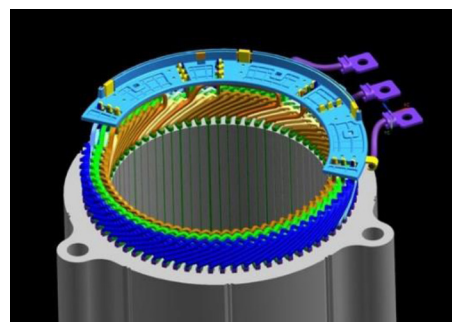
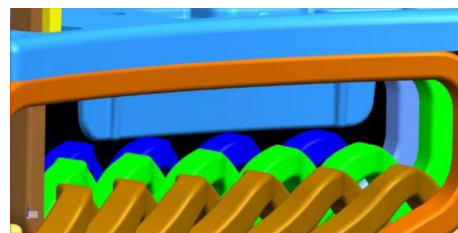


Figure 9. Modified stator slot geometry to make room for the two-piece slot-insulation

The Chevrolet Bolt BEV stator assembly includes a connection ring for the termination of the phase leads. The connection ring additionally includes neutral-bar for terminating the winding neutrals, and connection tabs for connection of the exit leads. This has made the winding lead termination scheme simpler compared to Chevrolet Spark BEV and resulted in a more robust manufacturing method. The connection rings along with few of its features are illustrated in [figure 10](#). Similar to Gen2 Volt stator design, the Chevrolet Bolt BEV stator design modulates the stator slot opening size and placement to optimize torque ripple and radial force. Additionally the stator optimization of the new design incorporates stator lamination rotation, which is typically implemented to eliminate bread-loaf effect, into the optimization of the slot-opening modulation. This resulted in a multi-variable, multi-step optimization and at the end provides the desired result with torque ripple and radial force reduction. The optimized stator lamination and the stator assembly of the new stator are shown in [figure 11](#).

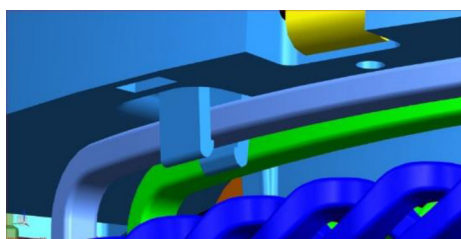


a.



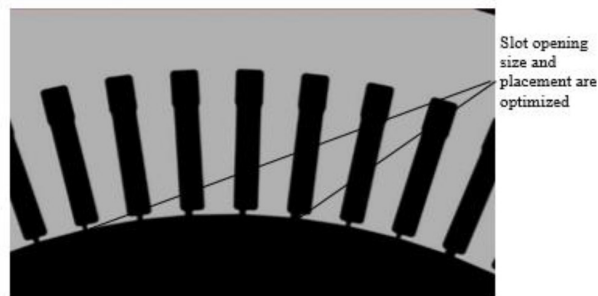
b.

Figure 10. The connection ring assembly (a), the locking feature (b), and the retention feature (c)

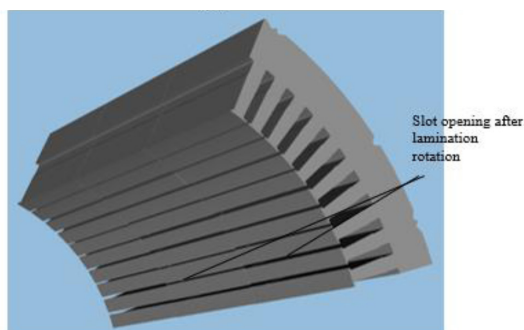


c.

Figure 10. (cont.) The connection ring assembly (a), the locking feature (b), and the retention feature (c)



a.



b.

Figure 11. Stator lamination with slot-opening optimization (a), Stator assembly with lamination rotation (b)

The result of this optimization on the torque-ripple and radial force are shown in [figure 12](#) for the peak torque speed operation of the electric motor. A sizeable reduction in both torque ripple and airgap radial force (calculated near the stator-teeth under a pole) is achieved, as shown in [figure 12](#).

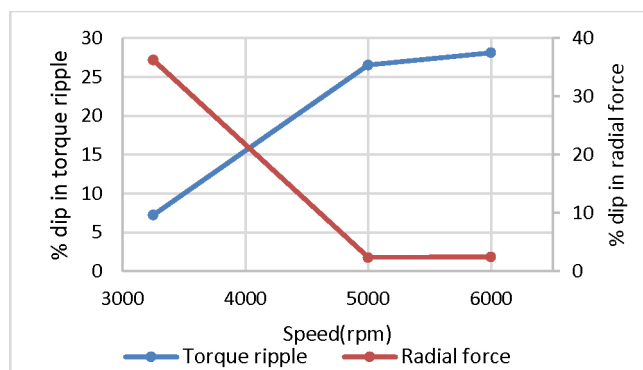


Figure 12. Reduction of torque-ripple and radial force with slot-opening optimization

Rotor Design

An interior permanent magnet rotor is optimized for the Chevrolet Bolt BEV electric motor. The magnets are placed under each pole in double layer 'V' arrangement. Sintered NdFeB type magnets are used for the optimization of the rotor geometry. [Figure 13](#) shows the optimized lamination geometry of the rotor.

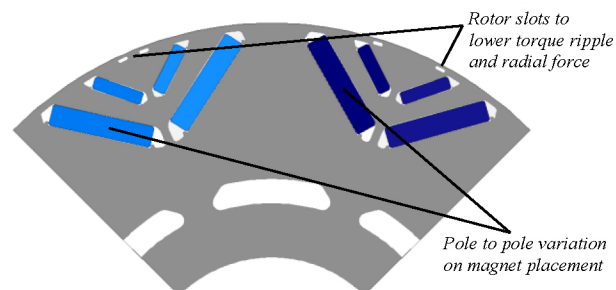


Figure 13. Rotor lamination geometry of the optimized rotor

The new design optimizes the magnet angular placement between subsequent poles separately. This has resulted in pole to pole variation in the magnet angular positions. The variation is subtle and not very noticeable in the design, however, has a pronounced effect on the reduction of torque ripple and radial force. Similar to Chevrolet Spark rotor design, the new design implements a pair of empty slot near the rotor OD. The placement and the size of the empty slot are optimized between subsequent poles. This resulted in further reduction of torque ripple and radial force.

The rotor and stator design features, introduced to mitigate torque ripple and radial force, allowed the new design to eliminate rotor skew with acceptable noise performance.

Final optimized motor parameters are shown in [Table II](#) and compares with the parameters of Chevrolet Spark BEV motor.

Table II. Chevrolet Bolt BEV Motor Parameter as a Comparison to Chevrolet Spark BEV motor

	New Generation BEV	Chevrolet Spark BEV
Peak Torque	360 Nm	540 Nm
Peak Power	150 kW	105 kW
Peak Power density	28.8 W/cm ³	18.5 W/cm ³
Peak Torque density	0.07 Nm/ cm ³	0.09 Nm/ cm ³
Max speed	8810 rpm	4500 rpm
Rated current	400 Arms	450 Arms
Motor stack length	125 mm	125 mm
Motor outer diameter	204 mm	213 mm
Number of poles	8	8

MEASUREMENT RESULTS

Figure 10 is a line graph titled "Continuous Thermal Performance, Max Winding Temp [C]". The Y-axis is labeled "Normalized Torque" and ranges from 0.2 to 1.0. The X-axis is labeled "Speed [RPM]" and ranges from 1000 to 8000. The graph displays multiple curves representing different winding temperatures: 100, 110, 120, 130, 140, 150, 160, 170, and 180 °C. The curves show that normalized torque decreases as speed increases and as the winding temperature increases. The 180 °C curve maintains the highest torque across the speed range, while the 100 °C curve maintains the lowest torque.

[illegible]

Figure 16. Chevrolet Bolt BEV motor transient (a) and continuous (b) thermal performance

CONCLUSION

This paper has presented the design details along with performance data of the electric propulsion motor of the Chevrolet Bolt BEV. Several improvements have been made successfully in the Chevrolet Bolt BEV motor. The new motor design has eliminated rotor skew, with the help of several rotor and stator design features, while maintaining acceptable noise performance. The number of conductors per slot has been increased to six from four of the previous designs.

This has resulted in improved joule loss performance at high speed operation of the motor. Slot insulation design also has been simplified with two-piece solution resulting in improved slot-fill. Continuous control of commutation through over-modulation to full six-step modulation is achieved without for full voltage utilization with stability intact. Overall the new design meets the performance and efficiency requirements with a lower cost motor which is easier to manufacture.

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ACKNOWLEDGMENTS

The authors would like to extend their thanks to many other dedicated engineers in General Motors for their valuable contributions toward the design and development of the electric traction motor.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AC - Alternating Current

BEV - Battery Electric Vehicle

PMSM - Permanent Magnet Synchronous Motor

SVPWM - Space Vector Pulse Width Modulation

EV - Electric Vehicle

HEV - Hybrid Electric Vehicle

PWM - Pulse Width Modulation

DU - Drive Unit

IPM - Interior Permanent Magnet