

The Voltec 4ET50 Electric Drive System

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ABSTRACT

General Motors' Chevrolet Volt is an Extended Range Electric Vehicle (EREV). This car has aggressive targets for all electric range with engine off and fuel economy with the engine on. The Voltec 4ET50 transaxle has gears, clutches, and shafts and controls that execute two kinematic modes for engine off operation or Electric Vehicle (EV) operation, and two additional kinematic modes for extended range (ER) operation. The Voltec electric transaxle also has two electric motors, two inverters, and specialized motor controls to motivate to execute each of those four driving modes. Collectively these are known as the Voltec Electric drive. This paper will present the design and performance details of the Chevrolet Voltec electric drive. Both the machines of the Voltec electric drive system are permanent magnet AC synchronous machines with the magnets buried inside the rotor. The motor has distributed windings. However, as opposed to a conventional stranded winding the Chevrolet Volt motor has bar-wound construction to improve the motor performance, especially in the low to medium speed range. At higher speed the skin effect and proximity effects in the stator bars lead to increased stator winding losses but are addressed in the design. The bar-wound construction also has excellent thermal performance in both the steady-state and transient conditions necessary for full EV driving. The generator uses concentrated windings. The concentrated winding construction has good slot fill and extremely short end-turn length. These features resulted in good performance in the intended operational region and were an enabler for machine packaging inside the transmission. Both the machines exhibit excellent efficiency and exceptionally smooth and quiet operation. Machine design and construction details as well as the measured thermal, electromagnetic and acoustic noise performance are presented in the paper. The

Traction Power Inverter Module (TPIM), which is designed to commutate these motors and uses state-of-the-art power electronic components, adopts flat and compact structure to achieve high current density and exhibits improved manufacturability. Hardware and software design tradeoffs were considered to meet TPIM reliability, efficiency, performance and overall security requirements. These features will be discussed in this paper. To address the aggressive targets for fuel economy and EV range of Chevrolet Volt, engineers were forced to closely examine all loss mechanisms involved in the electric drive system and optimize motor controls to provide the best drive system efficiency. While optimizing the drive system efficiency, other constraining requirements such as vehicle Noise Vibration and Harshness (NVH), high voltage bus ripple and resonance, component thermal performance and controllability, etc. were addressed. This paper will further discuss the issues encountered and solutions adopted to optimize the drive system efficiency to help the Chevrolet Volt meet the fuel economy and EV range targets.

INTRODUCTION

The main goals of GM's alternative technology vehicles are the reduction of emissions, the reduction of fuel consumption and the diversification of the energy sources. One way to reach these goals is by increasing the level of "electrification" [1]. GM was first in modern days to offer complete electrification when it's Battery Electric Vehicle (BEV) EV1 was introduced in 1996 [2]. Subsequently GM introduced hybrid electric vehicle (HEV), plug-in HEV (PHEV) and most recently, the Extended Range EV (EREV). An EREV has full functionality as an EV as long as battery has enough energy and hence provides more electrification than PHEV that has blended operation of gas and electricity and the

engine may be often forced on to support vehicle speed or power, even when the battery has plenty of useable energy[1]. As explained in [1], an EREV is very similar to the vehicle which was envisioned by the expert panels of Air Resource Board (ARB) in 2007 [3]. An EREV has zero emission vehicle (ZEV) mode when it runs as pure EV. GM is first among OEMs to produce EREVs.

Figure 1 shows Chevrolet Volt electric drive system context diagram. It has two machines. Motor-B is connected to the final drive and is mainly used as motor. Motor-A is connected with the engine and Motor-B through appropriate clutch configurations depending on the mode of control. Motor A is as motor in EV operation and mainly as a generator in ER operation. The Volt electric drive system also contains an oil pump motor. The oil pump motor supplies the oil, used for kinematic mode control, lubrication and coolant for the entire transmission system when the main hydraulic pump is off. The inverter module, labeled as TPIM, acts as a power conversion and distribution box between the HV battery and the motors. Volt TPIM has three power inverter modules (PIMs). Two main inverters, PIMA and PIMB, to run these traction motors and a third inverter, PIMC, to run the oil pump motor. These PIMs are voltage source inverters (VSI).

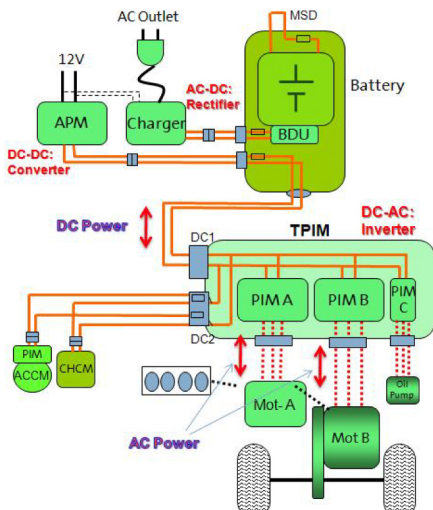


Figure 1. Chevy Volt Electric Drive Context Diagram.

Figure 2 shows a generic block diagram of a voltage source inverter (VSI) showing major building blocks. The VSI interfaces with HV battery, motor, inverter cooling system and the rest of the vehicle electrical systems and controls. The main building blocks of the VSI are the power modules, the DC bus capacitor, EMI filter capacitor, switching signals, motor controller. The motor controls algorithms are programmed into the motor controller.

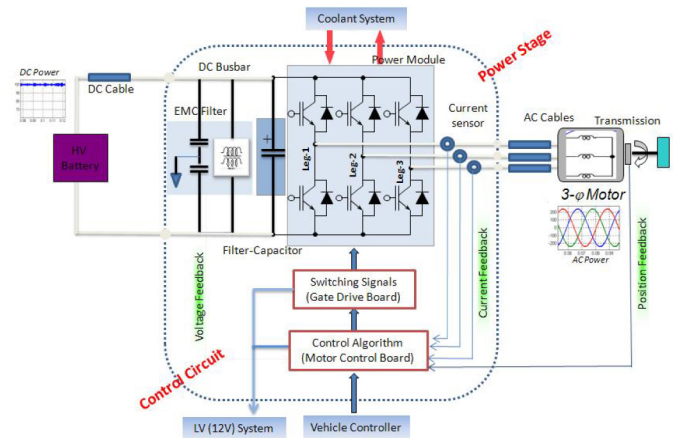


Figure 2. A voltage source inverter (VSI) showing major building blocks and system interface.

The Volt electric system has very aggressive targets for both all electric range and fuel economy. The traction drive efficiency is a large contributor to the overall vehicle performance. To meet these targets, engineers were forced to closely examine all loss mechanisms and optimize motor controls to provide the best drive system efficiency. However, the optimization the drive system efficiency was done within the other constraints presented, such as NVH, bus resonance, controllability. Hence, a trade-off involving input from various vehicle design disciplines was necessary. This paper will discuss the issues encountered and solutions adopted to optimize the drive system efficiency to help the Volt meet the fuel economy and EV range targets.

This paper is organized as follows: Volt traction machine design and construction will be addressed first. The power electronics drives designs will be described next followed by the motor control algorithm development. The final section would present some relevant test data. Summary and conclusion are presented at the end.

ELECTRIC MACHINES

Both the machines are buried (interior) permanent magnet ac synchronous machine type. The larger of the two machines is used mostly as an electric motor (to provide electrical propulsion or tractive effort) and is of a bar wound type construction. This machine is shown in figure 3 and is referred to as motor B in this document.



Figure 3. Motor B stator and rotor assemblies

The bar-wound construction, as opposed to the more conventional stranded type has several advantages, i) higher slot fill, ii) shorter end-turn, iii) improved cooling performance, iv) fully automated manufacturing process, v) improved high voltage protection etc. Some of these attributes would be elaborated later in this section. Due to bar-wound construction, the slots have parallel sides as opposed to stranded design where the tooth has parallel sides. This is illustrated in [figure 4](#).

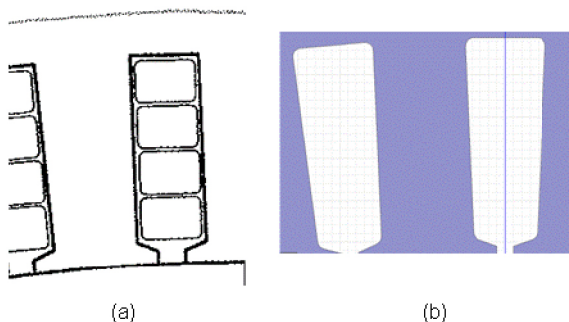


Figure 4. Slot shape of bar-wound (a) and stranded (b) design.

The winding layout of the bar-wound motor B has wave-winding construction whereas lap winding is typically used for stranded design. “Hairpin”s of the bar-wound construction are formed outside and then inserted in the slot. A twisting operation forms a frog-leg type shapes which are then welded together to form the wave-winding pattern. [Figure 5](#) shows a hair pin shape before and after insertion and twist.

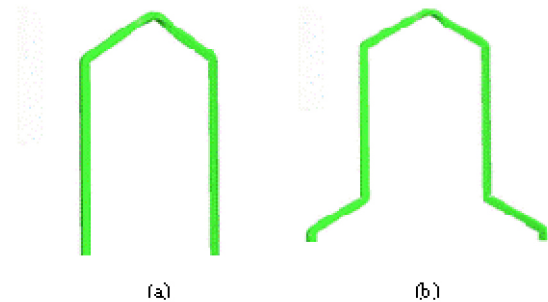


Figure 5. Hairpin shape before (a) and after insertion and twist (b)

The use of a bar-wound design on the Volt motor B allows the conductors to be designed with specific shaped coils and phases. As a result Volt motor B exhibits an excellent voltage protection. The amount hairpin width or span and the conductor width mostly dictate the end-turn height. Volt motor B has a small end-turn height which resulted in a larger active stack for the given packaging dimension. A cross section view of the Volt motor B stator and the end-turn region are shown in [figure 6](#).

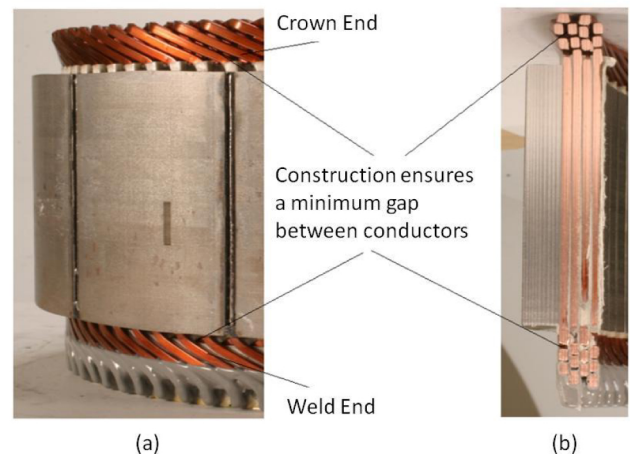


Figure 6. Cross sectional view of Volt Motor B showing the end-turn crown and the weld-end (a) and the detailed view of the conductors in the end-turn region (b).

Volt motor B has four bars (conductors) per slot as shown in [figure 7 \(a\)](#). The insulation system was further improved by the geometry of the slot insulation that provides isolation of the conductors from the stator laminations. This was accomplished through the use of a B-shaped insulator rather than a more conventional S shaped insulator as shown in [figure 7](#). This is an improvement from the earlier designs, GM Rear Wheel Drive two-mode hybrid, where an S-shape insulation paper was used. The B-shape provides better insulation by eliminating the gap in the corner that exists in an S-Shaped insulator between conductor and stator laminations.

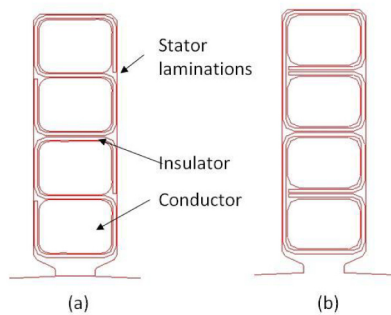


Figure 7. S-shape insulation (a) as used in GM Rear Wheel Drive 2-mode hybrid and the improved B-shaped (b) insulation as used in Volt motor B.

To provide further isolation between conductors, insulation material was inserted between layers on the weld end of the stator coils. The insulator between the two sets of conductors was made to protrude higher than the others to provide increased insulation between adjacent welds. To further make the bar-wound construction robust to manufacturing variation, the unique wire forms were coated with an insulating epoxy. This epoxy while providing an additional insulation coating.

The dc resistance of the bar-wound machine is significantly lower than the stranded design. This results from two facts as stated earlier, i) the slot fill of the bar-wound design is significantly higher than the slot fill of the stranded design, ii) the end turns are tighter for the bar wound design as compared to the stranded design. For Volt motor B, the phase resistance is roughly 30-40% lower than the equivalent stranded design which would produce the similar torque and power. However, the bar-wound construction would have significant skin and proximity effect which would increase the ac resistance of the machine at high speed. Figure 8 shows the ac resistance of the motor B as function of machine fundamental frequency and machine phase current. The conductor was sized properly to minimize the eddy current effect at higher speed. Hence, the skin effect in this particular design is not excessively high. Figure 8 also shows the phase resistance of an equivalent stranded design. It is assumed that the stranded design has no skin or proximity effect. This assumption is quite valid for machine built with multiple thin strands. Although the skin effect is computed as function of total phase current and machine speed, the skin effect actually depends not only on phase current but also on the split of the phase current between d-axis and the q-axis. Hence, it is a three dimensional function of d-axis current, q-axis current and machine speed.

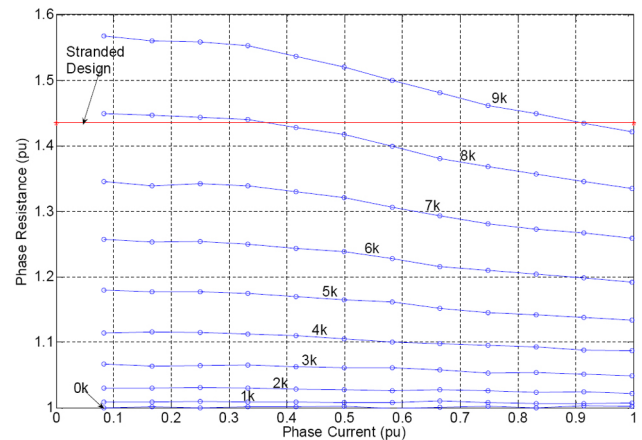
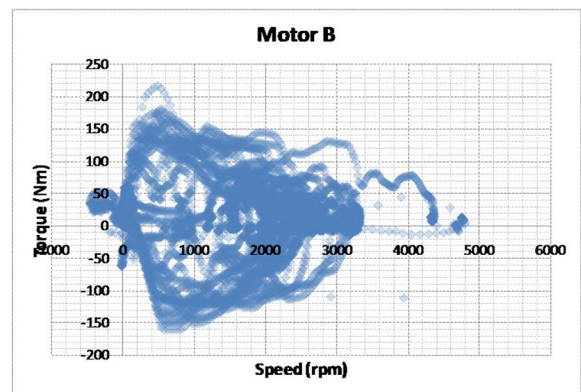


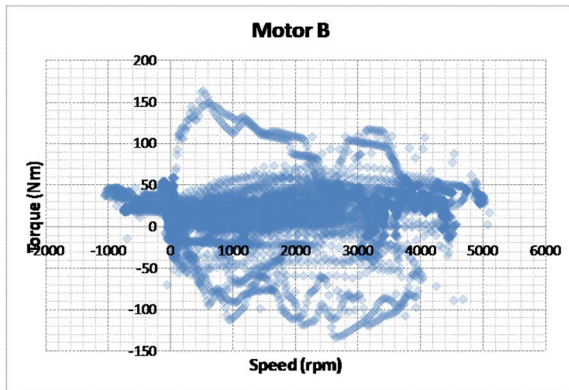
Figure 8. Machine phase winding ac resistance as function of phase current and machine speed.

It is evident from this plot that bar wound design has favorable winding resistance up to 8 krpm. Above that speed the stranded design starts to perform better than the bar wound design. Motor B usage profiles for most drive cycles show most significant motor B operation is all well below 8000 rpm above which bar wound starts to lose its advantage. Figure 9 shows the motor B usage profiles for the ftp urban 2 (a), highway (b), and US06 (c) drive cycles, where most of the motor B operations are below 5000 rpm where bar wound have its clear advantage over the stranded design.

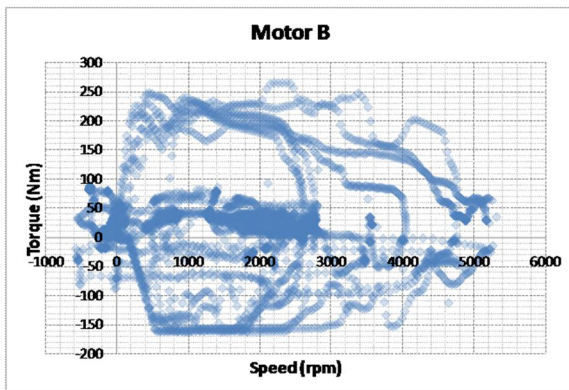


(a)

Figure 9. Volt Motor B usage profile (a) ftp urban2, (b) highway, and (c) US06



(b)



(c)

Figure 9. Volt Motor B usage profile (a) ftp urban2, (b) highway, and (c) US06

However, these usage profiles also show that there are significant motor B operations at light load areas at medium to high machine speed where the motor iron loss starts to dominate the total machine loss. Hence, reduction of machine iron loss was quite critical. This was addressed during the machine design, especially the rotor design.

Machine rotor of motor B has a V-shaped construction. This construction has favorable rotor saliency behavior, thus improving machine torque density. The rotor barriers, where the magnets are buried, are constructed with additional air pocket (barrier) on the top of the magnet. This is illustrated in [figure 10](#). The additional air pocket on top of the magnet acts as an air-gap to the magnet. Hence, addition of this air pocket reduces machine iron loss caused by the rotating magnet due to reduction in the airgap magnet flux. This additional air pocket also reduces the harmonic in the air-gap, thus, further lowering the iron loss due to rotating magnet. The addition of this air pocket reduces the d-axis inductance and hence improves the rotor saliency. As a result, reluctance torque of the machine is increased which to some extent offsets the loss of magnet torque due to reduction of the air gap flux. The

impact of the air pocket on the machine peak torque has been small.

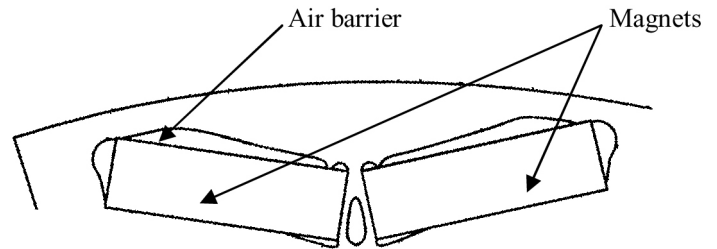


Figure 10. IPM Rotor Geometry of motor A.

The simulated unpowered iron loss of motor B is shown in [figure 11](#) as compared to a design without the air pocket where the iron loss for the machine with air-pocket is the reference. A significant reduction of machine iron loss has resulted due to the addition of this air pocket.

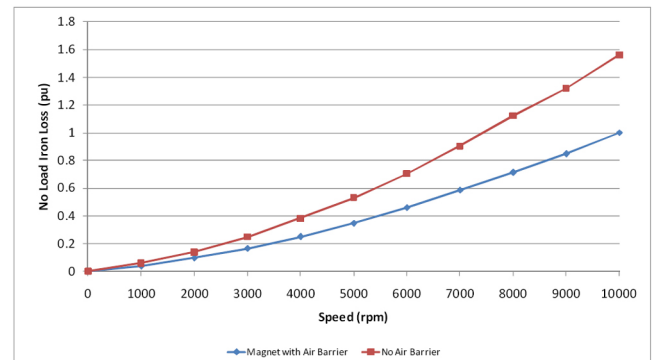


Figure 11. No load spin loss with and without air-barrier.

The other traction machine in the Volt drive system which mostly runs as a generator is a concentrated winding type. This machine is referred to as Motor A in this paper. The concentrated winding machine has significant packaging advantage and is well suited for limited space. Motor A rotor has 16 permanent magnet poles buried inside the rotor while the stator has 24 slots (teeth). An end view of motor A rotor is shown in [figure 12](#). Noise is a concern with concentrated winding machine. There are two major components for noise. One results from the pole passing frequency and the other results from the torque ripple frequency. The distribution of tooth forces as the pole passes the teeth is very critical for noise. The 24-16 geometry has an 8 lobe forcing distribution. [Figure 13](#) below shows the 8 lobe forcing distribution of the 24-16 geometry (which was selected for Voltec Motor A) and compares that to another geometry which has 4 lobe forcing distribution such as of a 24-20 geometry (20 pole rotor). 24-16 geometry has same peak level of tooth forces, however, more evenly distributed than the 24-20 geometry. Moreover, the eight-point pull of the 24-16 geometry as