

Next Generation Voltec Electric Machines; Design and Optimization for Performance and Rare-Earth Mitigation

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ABSTRACT

This paper presents the design and performance details of electric propulsion system for GM's second generation Extended Range Electric Vehicle (EREV). First generation Chevrolet Volts have been driven over half a billion miles in North America from October 2013 through September 2014, 74% of which were all-electric. The second generation of Volt brings a significant mass reduction and increased performance, EV driving range and fuel economy while simultaneously reducing rare earth content in its traction electric motors.

The electric propulsion system is built on two electric machines; both PMAC topology. While hybrid-electric vehicles are gaining in popularity in hopes of addressing cleaner, energy sustainable technology in transportation, materials sustainability and rare earth dependence mitigation has not been the first priority in the hybrids available on the market today. Design robustness to material cost volatility is crucial in automotive industry success and therefore designing electric propulsion to minimize or eliminate rare earth usage plays a major role in HEVs success. The objective of this paper is to present the newly redesigned propulsion system for added performance while simultaneously reducing the rare earth and heavy rare earth content by over 85% and 50% respectively and in turn the cost of the system and yielding all around "cleaner" and more sustainable vehicle. From an engineering point of view, this is a tall order by any measure so various technologies were utilized to achieve this goal. The paper will discuss grain boundary dysprosium diffusion process in permanent magnets as means to rare earth reduction in PMAC machines and design challenges surrounding such material use. We will also discuss innovative PMAC topologies employing ferrite magnets to completely eliminate rare earth usage while maintaining the electric drive unit performance. The design of electric machines will be discussed in detail along with performance measurement results as well as thermal and NVH aspects.

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INTRODUCTION

Although the idea of the vehicle power-train electrification dates back as far as an automobile itself, the internal combustion engine has dominated the automotive market over the last century. With more recent improvements in electric machines, battery technology and power electronics and with increasing awareness in environment and fuel consumption, the idea of combining the two propulsion means appears to be a reasonable solution and embraced by almost every automotive company in the world in hopes of addressing cleaner, energy sustainable technology demands in transportation. However, the key challenge facing the automotive industry in successfully implementing the HEVs and EVs remain the high sensitivity to weight and size of the components used. Attempts to keep this at bay have led to use of rare earth materials in HEV components in order to maximize the performance in a given package. The consequence of this approach makes the technology sensitive to material cost volatility having a crippling effect on vehicle electrification efforts. Of course, significant work is ongoing around the world on alternative technologies to reduce or eliminate rare-earth usage in

traction components for EVs and HEVs. In [1] Pellegrino et al. explored induction machines as an alternative to PMAC machines for EV traction application, however lower system efficiency, higher current requirement, rapid power drop off vs. speed, size and manufacturing issues are just some of the barrier in the way of induction motors for this application. Smaka et al. in [2] and Chiba et al. in [3] showed some promising results with switched reluctance machines in terms of efficiency improvements by careful design and material selections, however they overlooked a disadvantage of large converter needed to drive the SR machines and their major flaw of high torque ripple and exceptionally poor NVH performance. More recently, Rahman et al. in [4] examined a field wound synchronous machine for HEV application and while they showed good peak torque and high speed efficiency performance along with exceptional power capability, lower speed performance for city driving failed to compete with PMAC machine. Packaging is also an issue due to additional space needed for field excitation electronics. Many other authors have explored similar technologies in the context of EV and HEV traction application, but it suffices to say that PMAC machines have set a high bar in terms of performance to size and weight ratio

for all the competing technologies. However, their major drawback is use of rare-earth and heavy rare-earth materials making them a pricey commodity.

The work presented here deals with rare-earth material usage in electric machines for HEV drive train and preferred topologies utilizing Neodymium Iron Boron (NdFeB) magnets which contain rare earth material; Neodymium and heavy rare earth Dysprosium. Various design options and approaches to reduce or avoid rare earth materials in electric machines by employing new materials and topologies are considered. In particular we discuss innovative topology that takes advantage and enables use of ferrite magnets as an alternative to NdFeB as well as use of grain boundary dysprosium diffusion process in permanent magnets to significantly reduce the heavy rare-earth (Dy) and total amount of magnet at the motor level. The objective of this paper is not to merely compare electric machines of the previous and next generation Chevy Volt, but rather to show how different, more sustainable and cost effective technology can be used in place of rare-earth rich PMAC machines by carefully exploring system level requirements.

ELECTRIC PROPULSION SYSTEM CONFIGURATION

A key feature for the final design of the second-generation Volt propulsion system is its EV propulsion split between two motor-generators allowing for engine starting for extended range driving using torque from an electric machine used for traction, which makes the starts smooth, quiet and efficient and also helps to eliminate the mass of hardware that is not useful for EV driving. The use of two motor-generators 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. 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 [Figure 1](#) and its operating modes shown in [Figure 2](#). This enables two-motor EV mode in which the task of providing peak torque at low speed for crisp launch feel is split between its two electric machine. This is an important aspect of the drive unit design aimed at significantly reducing power and torque demand from electric machines yielding 20% volume and 40% weight reduction compared to first generation.

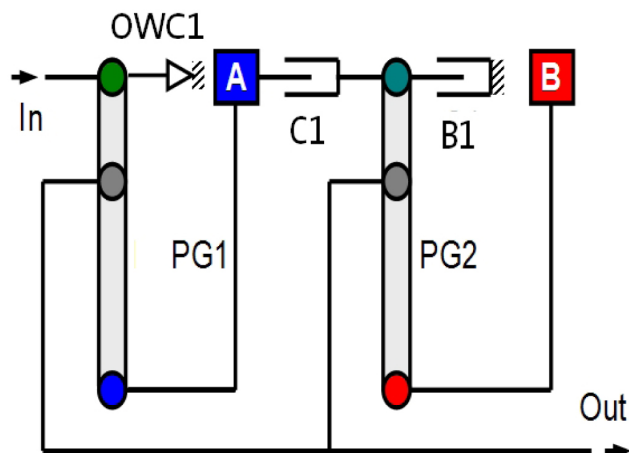


Figure 1. Drive Unit Power Flow

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

Figure 2. Drive Unit Power Flow & Operating Modes

ELECTRIC MACHINES

As described above, the drive unit consists of two electric machines A (smaller) and B (larger). Both machines are ‘bar-wound’. The bar-winding type has several advantages over the stranded windings; i) higher slot fill, ii) shorter end-turn which will enable longer active stack length of the machine improving the torque/ampere capability iii) improved cooling performance due the larger surface area in the end-turn which can be actively cooled as well as better copper to steel path, iv) improved high voltage protection and v) fully automated manufacturing process [5]. The winding layout of the bar-wound motor has wave-winding construction compared to lap winding in typical stranded design. Hairpins of the bar-wound construction are formed outside and then inserted in the slot. The conductors are then twisted and welded together to form the wave-winding pattern in a completely automated process. The selection of bar winding structure requires “parallel-slot” stator design, while the stranded windings would feature “parallel-tooth” stator design. The differences are shown in [Figure 3](#).

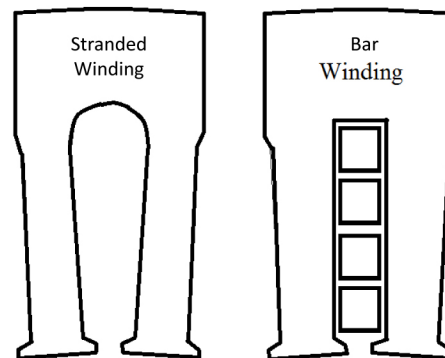


Figure 3. Stranded and Bar Winding Stator Slot Shape

The dc resistance of the bar-wound machine is significantly lower than the stranded design due to the slot fill and much shorter end turns which in turn will reduce the copper losses at low to medium speed operating points. The disadvantage is the increase of the resistance with current and frequency due to eddy effects i.e. skin and proximity effects, however with careful design optimization and considering the usage profiles of these machines [Figure 6](#) and [Figure 9](#) the benefits outlined above significantly outweighed this disadvantage.

MACHINE-A - FERRITE PERMANENT MAGNET ASSISTED SYNCHRONOUS RELUCTANCE MACHINE

Use of ferrite magnets in PMAC machine is not a new idea and it has been explored in the past, especially in recent years because of the volatility of NdFeB magnets. However most of the machines designed with these types of magnets are intended for use in industrial applications where requirements in terms of size, torque density and wide operating temperature range are not as extreme as in automotive traction application. For comparison, the ferrite magnets energy product ranges from 1.1 to 4.5 MGOe whereas the energy product of NdFeB magnets ranges from 18-33 MGOe. Consequently, the torque and power that can be expected from the ferrite machines would be significantly lower compared to those of NdFeB magnets. To bridge the gap, other ways of increasing the torque capability of the machine are explored. It is well known, shown in [equation \(1\)](#), that the torque of PMAC synchronous machines has two major components; magnet torque, first part of the [equation \(1\)](#) and reluctance torque, second part of the same equation.

$$T = \frac{3p}{2} [\lambda_d i_q + (L_d - L_q) i_d i_q] \quad (1)$$

There are several ways to enhance the magnet and reluctance torque components of PM machines. So called “flux focusing” machines or “spoke designs” are known to increase the magnet torque portion by combining and concentrating the flux of the two adjacent magnets as shown in [Figure 4 \[6\]](#). This type of configuration is most commonly used with weaker magnets such as ferrite. However this topology has some key manufacturing disadvantages with magnet retention and poor mechanical stress performance, making it only suitable for low speed operation. Additional concern of this type of design is the proximity of the magnets to the air-gap making them susceptible to demagnetization at higher operating current.

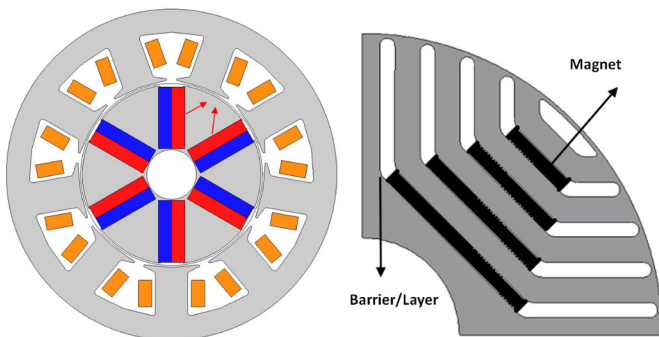


Figure 4. a.) Spoke Configuration Concept of PMAC Machine b.) Multi-barrier High Reluctance Permanent Magnet Assisted Synchronous Reluctance Machine Concept)

Another way of increasing the torque is by increasing the reluctance torque component of the machine, second part of the torque [equation \(1\)](#). This can be achieved in number of ways, mostly by varying the rotor geometry to increase the saliency of the machine i.e. increasing the difference between d-axis and q-axis inductance ($L_d - L_q$). Adding multiple magnet and air barriers, as shown in [Figure 4](#) to the rotor

geometry increases the saliency and in turn reluctance torque of the machine. This allows for less use of permanent magnet material or in this particular case use of weaker ferrite magnets. The topology is often referred to as Permanent Magnet Assisted Synchronous Reluctance Machine (PMASRM). It is worth noting that in practice a number of barriers that can be accommodated in the rotor may be limited by space or mechanical rotational stress. It was also shown in literature [7] a diminishing return on average torque increase by adding additional layers of barriers beyond four. It is relatively trivial to conclude that number of layers will impact the field interaction between stator and rotor and their relative harmonics which in turn will have an impact on torque ripple and NVH performance of the machine. To reduce the torque ripple it is recommended in [5] to select the number of barriers to satisfy the condition $Q/p + 1 \neq 2$ where Q is total number of stator slots and p is the number of poles. In this particular case with number of stator slots of 72 and 12 poles we selected 4 barriers. An optimized geometry of the A machine using ferrite magnets based on the usage profiles shown in [Figure 6](#) and balancing the magnet and reluctance torque components is shown in [Figure 5](#). Rounded, semi-circular barriers are selected over “square” shapes as they yield better performance in terms of both torque and iron loss. The machine exhibits very high saliency with 75% of its overall torque contribution coming from reluctance torque at peak operating current.

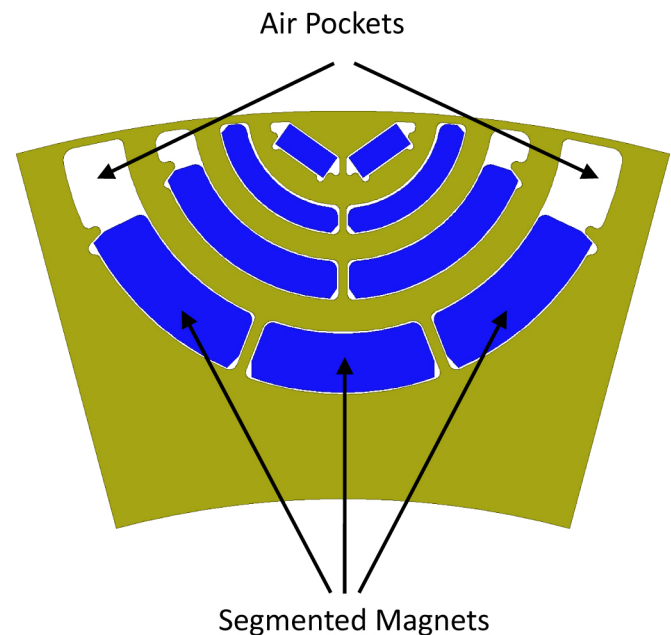


Figure 5. A Machine - Ferrite Permanent Magnet Assisted Synchronous Reluctance Machine

[Figure 5](#) also shows segmented (3 segments) magnets in the inner layer barrier which reduces mechanical stress at high speed on both lamination and magnets. [Figure 7](#) shows stress analysis at top speed. The 3 magnet segments are designed to be identical to reduce the cost and manufacturing complexity.