Automotive Electric Motors, Generators, and Actuator Drive Systems With Reduced or No Permanent Magnets and Innovative Design Concepts

DUE to environmental and energy concerns, electric vehicles (EVs) and hybrid EVs (HEVs) are gaining increased attention. At the heart of the drive system of these vehicles is the electric machine and drive. For these applications, high power density, high torque density, wide speed range, and efficiency are of primary importance. To meet these demands, interior-permanent-magnet (IPM) machines have been widely used. However, IPM machines use rare-earth PMs (usually neodymium–iron–boron magnets) in their structure. The price of these types of rare-earth PMs has increased by orders of magnitude over several years. Due to the high cost and limited supply of this material, the use of IPM machines in HEV applications is now being challenged. In fact, many researchers are working on other machines that can compete with IPM machines in terms of size, efficiency, power, and torque density. With consideration of the above points, there is a timeliness to this important topic; thus, we are pleased to present this "Special Section on Automotive Electric Motors, Generators, and Actuator Drive Systems With Reduced or No Permanent Magnets and Innovative Design Concepts" of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS that consists of 12 papers reporting on the most recent research on automotive electric drive machines. Most of these papers focus on machines with less or no rare-earth PM material in their structure, although control is also important, and there are some papers related to this topic.

In [1], a review of the different types of electric machines used in HEVs and EVs is presented. The authors summarize the efforts regarding reducing or eliminating the amount of rare-earth PM material used in electric machines. Induction machines, switched reluctance machines, PM-assisted synchronous reluctance machines (SynRM), claw pole machines, and flux switching machines are discussed for HEV applications. The paper puts the technology in context by addressing the related aspects of HEVs, such as the power split device and the hybridization index. Many novel types of machines are discussed, which are often hybrid machines, which are using PMs but also relying on reluctance torque. An emphasis is put on reporting the state of play of commercial vehicle drive motors. Many new vehicles are appearing with induction motor and reluctance motor drives.

It is possible to have magnetless drive motors, and there are several examples in commercial machines, as highlighted in [1]; these tend to be induction motors. However, leading edge research is being aimed at developing reluctance types of drive motors since they are rugged and have no rotor conductors; [2]–[4] report on these. Reference [2] addresses the design of a switched reluctance motor, which has the same outer diameter and stack length of the PM machine used in the Toyota Prius. This machine obviously contains no magnets. A prototype is built and tested. It is shown that the switched reluctance machine can generate higher power at high speeds, and in general, it is competitive to rare-earth PM machines. This paper directly addresses the need for alternative machines to be competitive in terms of the demanding performance required from an EV or HEV drive motor. The control of a switched reluctance machine is a key issue. This is coupled with a complex cycle in an HEV where it may be required to both motor and generate. Reference [3] analyzes a three-phase switched reluctance motor drive with integrated charging capacity for plug-in HEVs. The energy stored in the inductance of the machine is used for fast charging so that magnetizing energy is not wasted. In [4], a new SynRM with an epoxy-resin cast rotor and no iron ribs is proposed for variable gear EV drives. These machines have ducted rotors and run from a sinusoidal ac rather than a trapezoidal current as in the switched reluctance machine. The variable reluctance machine is therefore smoother. The motivation for this paper was to address the issue of position sensorless operation at zero or very small current values by increasing the saliency. Finite-element analysis and laboratory results are provided to validate the performance of the new design.

A second class of machines addressed in this Special Section is the machines with ferrite magnets rather than rare-earth magnets. This material is substantially cheaper, but its energy density is much less; therefore, this is a demanding design exercise. References [5]–[8] present work on various aspects of ferrite magnet motors when applied to automotive drive motors. In [5], an optimal design of a PM-assisted SynRM using ferrite magnets is discussed. The results are compared with that of an IPM machine with rare-earth material. The optimization goal is to improve the torque density and to reduce the torque pulsation of this machine. It is shown that the torque producing capability of the optimal PM-assisted SynRM with ferrite is only 15% lower than the IPM machine with rare-earth material, whereas the cost of the material is 50% less. This is a good illustration of the careful design necessary to utilize ferrite magnets in this

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application. In [6], a PM-assisted SynRM with ferrite magnets is designed for automotive applications. A scaled-down prototype is fabricated, and different performance metrics are obtained. The performance of a higher power machine is estimated based on the prototype, and it is concluded that the machine is suitable for HEV applications. In [7], a numerical process capable of predicting acoustic noise and vibration in an axial flux PM machine with ferrite magnets is studied. The Maxwell stress tensor method is used to calculate the electromagnetic forces. Natural frequencies and modal shapes are obtained using modal and harmonic analyses, and finally, vibrations and noise are predicted. The measurement results are compared by predicted values to confirm the validity of the model. It has been reported by other investigators that the power density of axial flux machines is good; therefore, this type of machine is worth investigating. However, vibration is important; this can be unacceptable in automotive drives because it can lead to mechanical and tire wear. In [8], spoke-type ferrite PM machines are discussed for EV applications. Finite-element analysis for two rotor design is presented, and mechanical properties are examined. Finally, a prototype machine is successfully tested.

Cooling in an automotive drive motor is vital. Forced fluid cooling is often used. The hot spots in the machine are the windings, and often, duty cycling is relied upon to ensure that the winding does not overheat. An effective cooling system can reduce the size of a machine; hence, even if a conventional rare-earth IPM machine is used, the magnet material can be less since the motor size is reduced. In [9], a cooling technique called the direct winding heat exchanger is proposed. In this technique, a microfeature-enhanced mesochannel is placed between the windings of an electric machine. By using the proposed heat exchanger, the thermal resistance from winding to ambient is reduced. It is shown that, by using this technique, the current densities during steady state and transient state can reach 24.7 and 40 A/mm2, respectively; therefore, electric machines with higher torque density can be developed.

Even if rare-earth magnets are utilized in the drive motors, careful design and the use of alternative designs can be used to reduce the amount of magnet material or make their use more effective. References [10]–[12] lie in this category. In [10], a PM machine with a sinusoidal PM shape, which is symmetric in the axial direction, is proposed. The sinusoidal PM shape will result in sinusoidal back-electromotive force and less torque pulsation. The proposed magnet shape will also eliminate the unbalanced electromagnetic force and therefore reduces vibration and noise. This machine uses less magnet material, whereas the low torque pulsation is highly advantageous in this application. The design is validated through a 3-D finite-element analysis and with laboratory measurements. In [11], a low-speed high-torque self-decelerating in-wheel PM machine for EV applications is presented. The proposed machine has two air gaps, less magnet material, and a relatively simple structure. This topology combines the advantages of a magnetic gear and a PM machine. In this paper, a sensorless control for speed estimation is also proposed. Reference [12] discusses a regenerative braking system for an EV driven by a brushless dc machine. By combining proportional–integral–derivative control and fuzzy control, mechanical braking forces and electrical braking forces can be properly distributed. Using this technique, the energy is recovered while the safety of braking is ensured. This will make the machine efficient, which is a prime criterion when designing automotive drive motors.

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