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Analysis and Development of Novel Three-Phase Hybrid Magnetic Paths Switched Reluctance Motors Using Modular and Segmental Structures for EV Applications

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***Abstract*—The classical switched reluctance motors (SRMs) often suffer from drawbacks such as low power and torque densities, high torque ripple, mutual coupling, etc., which limit their industrial applications. This paper presents the analysis and development of two novel three-phase SRMs with hybrid magnetic paths comprising six E-shaped modular stators and three segmental common rotors, termed as the modular SRMs (MSRMs), for electric vehicle applications. The machine topologies with different winding arrangements are described. The voltage and output power equations are analytically derived, and some design particularities and parameters are discussed. The field distributions and static magnetic characteristics of an MSRM with double coil are analyzed by using 3-D finite-element method. After that, two MSRMs with different winding arrangements, namely a double-coil MSRM and single-coil MSRM, are analyzed and compared to evaluate the distinct features of this novel MSRM, accompanied with a classical three-phase 6/4 SRM. The comparison includes static magnetic characteristics, mass of iron core, normal dynamic, and fault-tolerant performances. It is shown that the double-coil MSRM appears to have better characteristics such as higher torque production capability, lower torque ripple and cost, higher torque and output power densities, and higher reliability and fault tolerance. For experimental verification, laboratory testing of a double-coil MSRM is developed, and the simulated and measured static inductance characteristics and dynamic performances correlate well.**

***Index Terms*—Double coil, hybrid magnetic paths, single coil, switched reluctance motor (SRM).**

I. Introduction

WITH the development of electrical and mechanical engineering, more and more novel mechatronics systems, such as carbon nanotube shuttles, brushless dc (BLDC) motors, piezoelectric rotary motor, actuator system, and multidisk spherical electromechanical brake [1]–[5], have been applied for industrial purposes. Switched reluctance motor (SRM) is a variable reluctance stepping motor that is developed to efficiently convert energy. Although the structure of the SRM is similar to that of the step motor [6], [7], it has the following features that are different from the step motor: fewer poles; larger stepping angle; usually one tooth per pole, higher power output capability, etc. The SRM is gaining widespread interest as good candidates for many applications such as electrical aircraft, electric vehicles (EV), wind turbines, etc., due to its simple structure, ruggedness, high starting torque, ability of fault tolerance, high-speed operation, and low manufacturing cost [8]–[10]. However, its disadvantages are also obvious: such as low power and torque densities, high torque ripple, mutual coupling, etc., which limit their industrial applications.

There are several efficacious methods have been investigated to improve the SRM drive system and make it more meritorious to industrial application, which can be sorted into three classifications. The first way is an easy way, which is to increase the stator/rotor pole or phase numbers in SRMs. In [11]–[13], design considerations and comprehensive evaluations for SRMs with a higher number of rotor poles for the drivetrain have been presented. Owing to the higher number of poles, the conduction time in each phase current period is much smaller than the classical SRMs. The static torque production capability is much better and the torque ripple is lower than the classical SRMs. The second method is to optimize the control strategies for the SRM drive. The torque ripple can be minimized by finding an optimum current profile, and then, following that through a high-bandwidth current regulator. Various current profiling and phase torque distribution methods to minimize the torque ripple appear in the literature [14] and [15]. Another method to minimize the torque ripple is called as the direct instantaneous torque control. It uses novel converter and does not require any current profiles for shaping the phase currents or torque profiles and commutating waveforms. It only uses simple control schemes of torque hysteresis control to reduce the torque ripple [16], [17]. The third method is to employ the redundant technique in the SRM topology. In [18], a novel dual-channel SRM (DCSRM) was proposed for high reliability operation by dividing the windings into two symmetrical three-phase winding units in an classical 12/8 SRM topology. In this connection, a winding or phase fault in one channel will not influence the operation of the same phase in another channel or of other phases. This DCSRM is a redundant machine, which is suitable for developing integrated

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