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A Review on Low-Noise Switched Reluctance Motors in Electric Vehicle Applications

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Abstract:
This paper presents a technical overview for low-noise switched reluctance motor (SRM) drives in electric vehicle (EV) applications. With ever-increasing concerns over environmental and cost issues associated with permanent magnet machines, there is a technical trend to utilize SRMs in some mass production markets. Switched reluctance motor is the simple as compared to electrical machines in constructional point of view. Its advantages are easy structural simplicity, highly reliable and low cost. Nowadays the pollution of the environment is increasing due to conventional vehicles. Hence, to reduce the pollution electric motors are very beneficial. Presently use of high power density magnetic motors like, brushless DC (BLDC) motors and permanent magnet synchronous motors (PMSM) have been the primary choice in the EVs and HEVs. But these motors have problems with demagnetization, high cost and fault tolerance. Therefore, in future permanent magnet motors will be replaced with SRM for EVs and HEVs. Because of SRM have no permanent magnets on the rotor, higher torque to power ratio, low losses and low acoustic noise compare to BLDC motors and PMSM. This paper is based on the special electric motors for example design & performance, motor structure, control strategy, comparison, noise and efficiency. It is our aim that this paper provides the guidelines on performance for low-noise SRM drives in EV applications.

Keywords: Switched reluctance motor (SRM), low noise, motor structure, control

I. INTRODUCTION

In hybrid and pure electric vehicles, permanent magnet motors are widely used because of their compactness, high efficiency and high torque density [1]. Nowadays conventional vehicles produce air pollution throughout their life, during the vehicle operation. The most important pollutants from conventional vehicles are sulfur dioxide, Hydrocarbons, Carbon monoxide, Greenhouse gases and Nitrogen oxides.The rare-earth problem is still one of the main concerns for automotive manufactures because the volume of hybrid and pure electric vehicle production has been increasing these days. Among competing for motor technologies, switched reluctance motors (SRMs) have received growing attention for both industry and research community due to the rare-earth-free characteristic and excellent performance.The SRM provides a longer examination time in unkind environments a supplementary cost effectual motor drive operation than BLDC motors and PMSM. The SRM has lots of reward like, good efficiency, good reliability and more starting torque in early accelerations, excellent fault tolerance ability. The permanent magnet (PM) machines have beneficial that makes suitable for EVs and HEVs. But, the available resources of PM materials are limited and cost effective. Their advantages include simple structure, low cost, robust configuration, and fault tolerance ability, making them suitable for high-speed, high-temperature, and safety-critical applications, such as EV/HEV [2]-[3], aircraft [4], and home appliances.This source of noise needs to be mitigated if the motor is employed for a high-performance EV application.

II. DESIGN

Fig. 1 shows the classification of possible improvements on the radial force and tangential force for the developments of motor topologies and control strategies, which will be analyzed in details in the following sections.

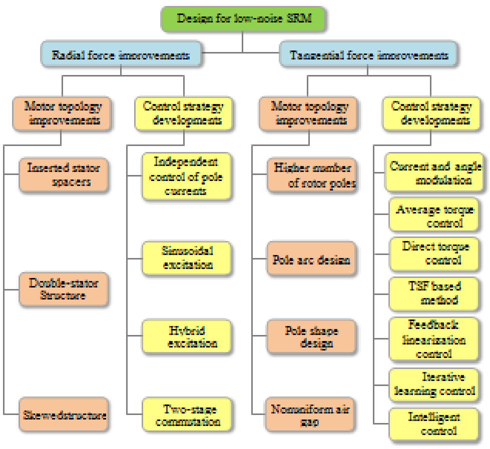
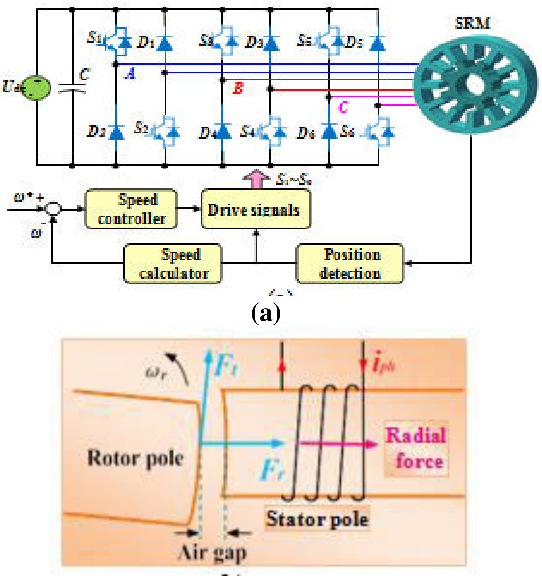


Figure.1. Classification of possible developments for low-noise SRM drives.

III. SRM DRIVE & ELECTROMAGNETIC FORCE

Fig. 2(a) shows a typical three-phase 12/8-pole SRM drive, where the conventional asymmetric half-bridge converter is used to drive the motor.



(a)

(b)

Fig. 2. SRM drive and attraction force. (a) Three-phase SRM drive. (b) Attraction force produced by stator and rotor poles.

IV. MOTOR STRUCTURE

In [5], the traditional slot wedges in SRMs are exchanged by structural stator spacers, which are made of stiff nonmagnetic materials (preferably ceramics). Fig. 3 shows the stator structure with and without structural stator spacers in a four-phase 8/6-pole SRM. This modification to the stator laminations can reduce the vibration and secure the windings. A simple design of a cylindrical rotor is proposed in [6], by connecting the salient poles with thin ribs, to reduce the acoustic noise at high rotational speeds. An investigation of vibration and acoustic noise is presented in [7] by analyzing the material and structure of the stator frame, and an optimization method on the motor structure is provided. In [8], acoustic noise reduction by designing frame thicknesses and shapes are investigated for high-speed SRMs. Compared to the conventional motor structure, a double-stator SRM (DSSRM) is proposed to reduce the radial forces in machines [9], [10], as shown in Fig. 4. The rotor is assembled between the inner stator and outer stator, and the attraction force is generated on the rotor pole from the inner and outer stators. The double-stator configuration and magnetic force of the DSSRM are analyzed in details in [9]. The structural behavior of a DSSRM and a conventional SRM is compared in [10], by using multi-physic analysis, which illustrates an obvious reduction in vibration.

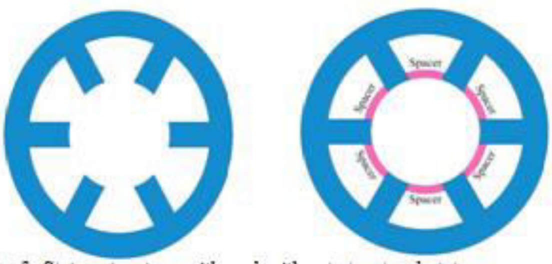


Figure. 3. Stator structure with and without structural stator spacers (a) Conventional stator. (b) Developed stator [28].

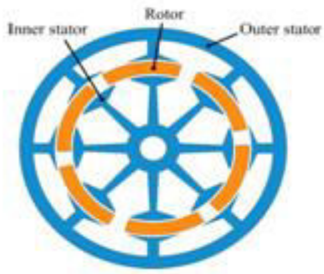


Figure. 4. Double stator SRM structure [32], [33].

The stator and rotor poles of SRMs can also be improved to reduce the radial force. A single-phase SRM by skewing the stator and rotor poles is developed in [11], and the acoustic noise and vibration are investigated and compared under different skewing angles. From this work, it can be seen that proper skewing can effectively mitigate the acoustic noise and vibration for SRMs. The skewing technology is also employed for linear SRMs in [12], and the optimal skewing angle is investigated by using the finite element method (FEM). In [13], skewing effects on both stator and rotor poles for a three-phase 12/8 SRM are investigated by the authors, and the motor structure is illustrated in Fig. 5. Different skewing technologies are presented, and the radial force, torque, and efficiency are compared in details. From the results, it can be concluded that skewing the stator pole is a more effective way to reduce the SRM vibration than skewing the rotor pole.

(a) (b)

Figure. 5. Skewed motor structure [36]. (a) Skewed stator. (b) Skewed rotor.

V. CONTROL STRATEGY

A. Control of pole currents

As illustrated in Fig. 6(a), a phase winding for a three-phase 12/8-pole SRM is composed of four pole windings, i.e., $A1$, $A2$, $A3$, and $A4$, which is connected in series. In [14], a controlled radial force scheme is proposed. In this scheme, the torque is controlled by the traditional method, i.e., the same current is applied to all the poles in the excited phase to produce the desired torque. The radial force and torque can be separately controlled when all the pole currents are independently controlled, as shown in Fig. 6(b). In [15], a sinusoidal current excitation method is presented for the radial force control of SRMs based on the independent control of pole currents, as shown in Fig. 6(c). Two additional poles from the descending-inductance phase are energized to generate the desired radial force. However, the negative torque will generate in this case, and some torque produced by other poles will be cancelled out.

B. Hybrid excitation

The motor is excited by combining one-phase excitation and two-phase excitation. In the torque generation region, the next phase is excited before the turn-off angle of the previous phase, and thus a low vibration can be achieved in the overlapped excitation region. A hybrid excitation method for SRM is proposed in [16] to reduce the radial vibration force and acoustic noise.

C. Commutation of two stages

A two-stage commutation strategy is proposed in [17]-[18], In asymmetric half-bridge converters, the upper switch and lower switch are both turned off in the non-conduction region, and the current goes back to the power supply quickly under a negative bus voltage, where recovering energy to the power supply is achieved. When the current reaches the turn-off angle, the upper switch is turned off and the lower switch remains on instead of turning off compared to the conventional scheme.

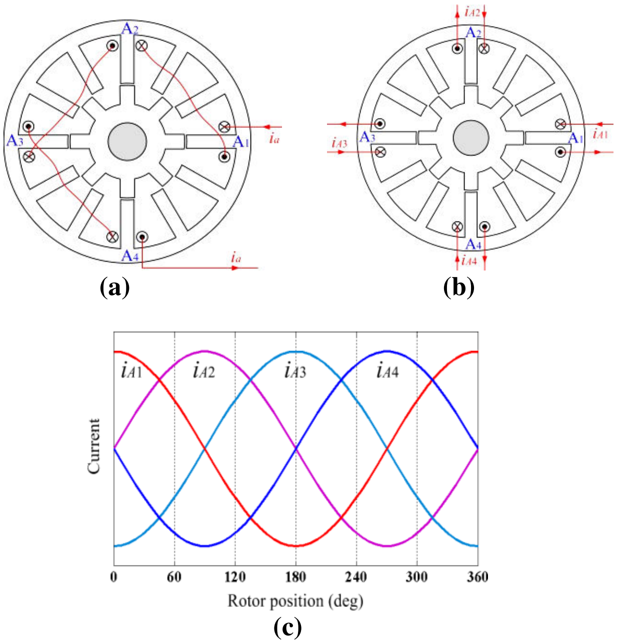


Figure.6. Independently controlled pole currents. (a) Series pole windings. (b) Independent pole windings [19]. (c) Sinusoidal excitations [20].

VI. COMPARISON

A. *BLDC Motor & PMSM*

The excitation required for PMSM and BLDC motors are generated by PM in the rotor part of the system. Due to high energy density of the PM, these motors get more advantages such as PM requires less space. Iron losses in one of the important losses in the PMSM and BLDC motors. The overload capacities of BLDC motor and PMSM are limited by using magnetic characteristics. Fig. 7 shows the torque speed curve of PMSM used in EVs. During the nominal speed, the overall efficiency of the BLDC motor and PMSM are high due to zero excitation current in the system. Iron losses in one of the important losses in the PMSM and BLDC motors. During the constant torque region of the PMSM, rated speed is not reached, and constant torque is exerted.

2.SRM

This principle is not applied in the advancement in the power electronic applications. Compare to conventional motors, SRM shows improved power density and also it has good efficiency. The construction achieved better charges. The construction of SRM is very simple such that it has concentrated stator winding without any rotor winding. The torque speed characteristics of SRM are shown in Fig.8. Here ω_b is called as base speed and it is defined as the speed at which peak current can be provided to the motor rated voltage with constant switching angle. Based on the rotor position, the current in the stator winding are switched ON and OFF. The natural region is the one which have constant frequency and constant switching angles.

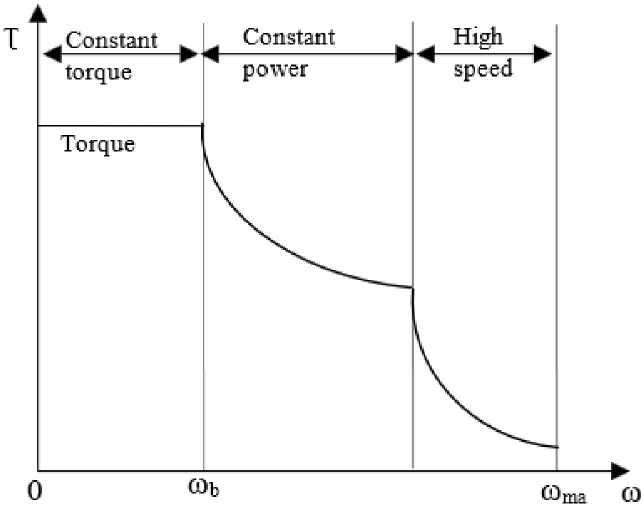


Figure.7. Torque speed characteristics of PMSM

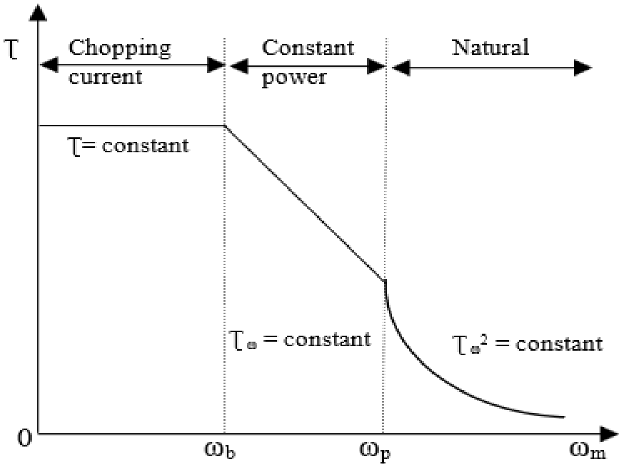


Figure.8. Torque speed characteristic of SRM

VII. DIFFERENCE FROM TECHICAL POINT OF VIEW

From Table I, the best placed challenger is switched reluctance motor drives. Here higher number of digit is good for the selection of EVs and HEVs applications. After analysis that we selected a SRM because simple construction, ruggedness and manufacturability are very significant qualities for mass manufacture of motor drives for electric vehicles.

Table.1. Comparison of special electrical motors

Items	Maximum	BLDC motor	PMSM	SRM
Power density	10	9	10	8
Overload	10	7	7	8
High speed range	20	9	10	8
Control	20	15	15	16
Noise	10	8	8	6
Torque ripple	10	6	8	5
Size and weight	10	8	9	7
Ruggedness	20	14	12	18
Maintenance	10	8	8	9
Manufacturing	20	14	12	18
Cost	30	20	18	26
Total	180	128	135	146

VIII. CONCLUSION

EVs and hybrid EVs have received increasing attention to reducing the fossil energy consumption and carbon-dioxide emissions. SRMs are gaining much interest for EVs and hybrid EVs due to the simple and robust structure, high reliability, and rare-earth-free feature. However, the acoustic noise problem caused by its inherent structure restricts further developments. For high-performance vehicle applications, it is very important and urgent to optimize the SRM system to reduce the noise and vibration. To present clear solutions to the noise reduction in SRMs, this paper gives a scenario on the electromagnetic forces to explain the mechanism of the SRM noise, and then reviews for the acoustic noise reduction. It concentrates on the motor structures including stator & rotor. The adopted methods for control techniques and limitations of these schemes are summarized and compared in details. Furthermore, the techniques that have been proposed by the authors are also presented and discussed, including the motor pole skewing scheme. Therefore, this paper presents performance of low-noise SRM drives in EV applications. From the review results, it can be found that many efforts have been made to optimize the motor topology by designing the new stator and rotor. However, the structure complexity and production cost are increased. Compared to the motor topology design, improving the control strategy is a more cost-effective and flexible way to deal with the acoustic noise in SRMs. Although the comparison between SRM & BLDC significantly indicates performances such as torque and efficiency are increased in SRM. Also, control strategies mainly focus on either low-speed or high-speed operations, while the noise and vibration reductions over a wide speed range have not been effectively achieved. The SRM migrates the advantages of a brushless DC (BLDC) motor and permanent magnet synchronous motors (PMSM) though considerably developing its high-power density, high torque, low vibration and low acoustic noise compared to other motors. Based on a complete relative study, it has been shown that SRM is better compare to BLDC motors and PMSM in applications of EVs and HEVs.

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