Switched Reluctance Machines and Drives for High-Performance EVs – A Review

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***Abstract* - Switched reluctance machines are considered as serious candidates for high-speed electric vehicles. This paper reviews the functionalities and merits of switched-reluctance machines (SRM) and drives for high-speed electric vehicles. The essential operational characteristics and design parameters w.r.t high torque density, high power density, wide operating range and a high, maximum speed capabilities, are described. Features and applications of switched reluctance machines and drives are discussed w.r.t automotive applications. The operational issues relating to commutation, acoustics, vibrations are discussed. Finally, the control and operation of SRM in the constant power region are detailed.**

I. Introduction

The concept of Switched Reluctance (SR) machines was established in 1838, but it was only in the mid-1960s it had started to achieve its full potential, with the development of modern power electronics and computer-aided electromagnetic design. The SR machines are doubly salient, singly-excited motor, which means both stator and rotor exhibit saliency but only one member (usually the stator) carries the windings. The rotor does not have any winding but is made of stacks of laminations. Excellent performance and low manufacturing cost make SR motors a vigorous competitor to both induction-motor drives and DC commutator drives, as well as PM brushless DC motors. Simple and rugged construction along with no requiring permanent magnets make SRM cheap to manufacture. The cooling is more accessible owing to bulk of windings, hence the heat, appearing on the stator. Torque is independent of polarity of current, reducing the number power switches required in the converter circuit. The direction of operation can be changed by merely changing the excitation sequence, making four-quadrant operation possible. The SR motor also has some clear disadvantages. The most important of which is the non-uniform torque, which leads to torque ripple and may contribute to acoustic noise.

This paper is organised in five further sections and reviews the design, operation and control, automotive applications, drives, acoustic noise and vibrations in SR motors. Section II presents the principles and the recent advancements in the design, analysis and modelling of SR motors for EV applications. In Section III, converters and the drives are discussed. Section IV deals with the control strategies and methods advancements in reducing acoustic noise are also discussed. In Section V, automotive applications of SR motors and its operation in constant power region is discussed. In this section, the high-speed region, beyond the constant power region, is also discussed.

II. MODELLING, DESIGN AND ANALYSIS

The first step in designing any machine is its accurate modelling and determination of operating and design parameters. The laws of electromagnetism and electromechanical energy conversion govern the operation and design parameters of SRM. Due to double saliency, the machine has nonlinear current in the windings, making the design much more complicated than conventional singly salient machines.

The reasons which justify, and hence require extreme care in design, the choice of SRM for electric propulsion are high torque and power densities, extensive speed range, quick response, and high efficiency and keeping these objectives in mind, the design methodologies for an SRM for electric propulsion applications can be broadly classified as, 1. Analytical method, 2. Finite Element Analysis, and 3. Optimisation method. In this paper, the first two methods are discussed, and two novel designs for SRMs using FEA is presented.

1. *Analytical method*:

Earliest machine analysis was done using analytical methods. Analytical methods can be divided into linear modelling and non-linear modelling-based methods. Linear methods utilise the Maxwell's EM equations and current independent parameters to determine the flux linkages vs current characteristics of aligned and unaligned rotor positions to justify the design. The non-linear modelling involves current dependent parameters, like magnetic saturation of the core into account, as well to develop flux linkage vs current characteristics.

Ray and Davis [1] presented a method to linearise phase inductances which allowed voltage to be switched at any point in the cycle. This allowed control strategies to be developed and examined for SRMs with sufficient accuracy. Krishnan and Arumugam [2] developed a procedure for the design of SRMs which is based on using output equations, thereby bringing the design engineer's experience to bear on this new machine.

The nonlinear modelling method is done by considering the magnetic saturation of the core, especially during fully aligned position. Various researchers have attempted to develop a comprehensive machine model using non-linear modelling methods through geometric studies that included aspects like multiple teeth per stator pole, tooth width to pitch ratio, etc. Radun [3], Finch [4] and Mao et al. [5] have presented an approach to develop an analytical model to calculate, accurately, the air gap flux and phase inductances in various degrees of overlap. These modes require only the machine geometries and material parameters to develop simulation models for machine performance determination. In Radun and Mao paper, the stator and rotor geometries are reshaped into rectangular structures to simplify analysis in Cartesian coordinates. Radun paper uses Fourier series expansion of Maxwell's equations to determine flux linkage for various degrees of rotor-stator overlap. In [6], this method is generalised to all rotor angles by assigning flexible boundary conditions and basing the formulations on polar coordinates to improve accuracy compared to rectangular structures.

2. *Finite Element Analysis*

Finite Element Analysis (FEA) is a general and advantageous method for rapidly solving nonlinear field equations within the motor. The FEA divides the entire solution domain into smaller, simpler parts, called finite elements, by a process called meshing. The equations associated each finite element is then combined into a larger system of algebraic equations. With improvements in processing speed and memory capabilities, FEA methods have become the go-to tool for designers and researchers alike to develop accurate models for SRMs. Dawson utilised two-dimensional FEM and the principle of virtual power to analyse the torsion of an SRM drive system and made a comparison experimentally, indicating that the torsion vs rotor angle performance can be accurately predicted using FEM [7]. A novel two-phase homopolar SRM was analysed and presented by Mi Ching Tsai et al. [8]. Faiz and Zadeh also study the static model of the SRM, and the results indicate accurate resemblance to FEA results. A new stator pole face with non-uniform air gap with a pole shoe attached to the rotor has been introduced to reduce the torque ripple [9][10]. A study of five different stator lamination stacks was carried out in [11][12] using three-dimensional FEM. Analysis results show that trapezoidal pole with hexagonal-round yoke is presented to reduce the vibrations from magnetic force.

In a study done by Xu et al. [13], a 12/8 SRM with segmental rotors is developed. The machine design presented here makes use of hybrid stator pole type stator and segmental rotors. This shortens the flux path and eliminates the flux reversal in the stator pole. Thus, compared to conventional SRM design, there is reduced magnetomotive force requirements and improves the electric utilisation.

Fig. 1 shows the proposed 12/8 SRM. Unlike conventional designs, the stator of the proposed structure is comprised of two types of stator poles, main and auxiliary. The main poles are wound by windings and generate the main flux. The auxiliary poles do not have any windings but are there to provide the flux with a comparably shorter return path. Furthermore, the rotor is constructed on a non-magnetic isolator with series of discrete rotor segments. The rotor segments are embedded in nonmagnetic isolator and are isolated from other segments.

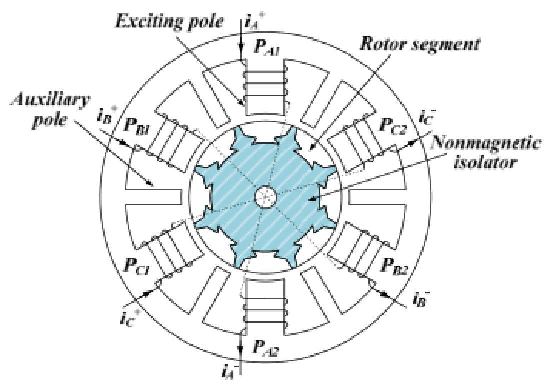

Fig. 1: Novel segmental rotor type 12/8 SRM. [13]

To verify the proposed design, as shown in Fig. 1, the machine was developed, and the performance was compared against conventional 12/8 SRM, experimentally. To precisely evaluate the machine performance, considering the saturation of magnetic materials under full load conditions, FEA is employed. Some of the key results are:

- Higher average torque for all values of phase excitation.
- Fast response.
- Excellent running stability.
- Reduced number of turns.
- Higher running efficiency.

A novel SRM design using a newly developed pole design formula in a paper presented by Desai et al. [14] have been proposed. The new PD formula is $N_r =$

$2N_s - 2,\ N_s > 4$. This formula results in a higher number of rotor poles than stator poles. In this study, using FEA a 6/10 SRM is simulated and the performance is compared to a conventional 6/4 machine having same air gap length, stator and rotor outer diameter and stack length. The operation of the proposed 6/10 machine is like that of conventional 6/4 SRM. The opposite poles of stator constitute a phase. On the application of excitation, each phase pole can potentially attract two rotor poles, but the degree of attraction depends on the angular distance of a rotor pole from the excited pole. The closer rotor pole (i.e. 12° away) experiences a stronger attraction as compared the pole that is 24° away. This prevents any dead zone and results in continuous rotation, and the machine can start at any position.

The angular travel per stroke for the 6/10 machine is 12° compare to 30° for conventional 6/4 test machine. This leads to higher fundamental frequency, and a higher number of strokes per mechanical revolution, which is an advantage as the average torque produced is proportional to the magnetic coenergy and the number of strokes.

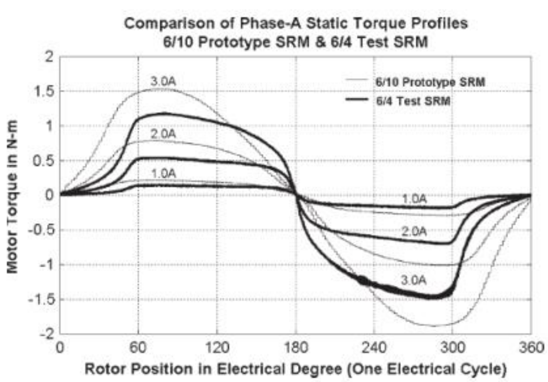

Fig. 2: Comparison of static torque profiles of 6/4 and 6/10 SRM. [14]

Fig. 2 shows a comparison of static torque profiles of phase A of 6/10 and 6/4 SRM at various current levels. It can be observed that for almost all rotor positions, the torque produced is higher for the 6/10 machine. This is owing to the 8% more winding turns and higher stroke factor. The proposed 6/10 machine there is a 30-47% increase in peak torque and 24-51% increase in average torque with comparable torque ripple. Due to an increase in the number of rotor poles compared to stator poles, these configurations have shown superior performance with higher torque per unit volume, comparable torque ripple and lower manufacturing costs, making this novel design a solid contender for high-performance automotive applications.

TABLE I

COMPARISON OF TORQUE FOR OPTIMISED 120° (ELECTRICAL) CONDUCTION [14]

Comparison of Torque Quantities: For 120° (Electrical) Conduction Interval (With Optimized Turn ON & OFF Angles)				
Factor	Phase Current (A)	6/4 Test SRM	6/10 Prototype SRM	% Difference
Peak Torque (N-m)	0.5	0.04	0.06	31.65
	1	0.15	0.22	42.85
	1.5	0.32	0.47	46.74
	2	0.55	0.79	44.46
	2.5	0.84	1.16	37.68
	3	1.18	1.53	29.49
Average Torque (N-m)	0.5	0.03	0.04	43.93
	1	0.13	0.19	50.64
	1.5	0.27	0.41	49.39
	2	0.47	0.68	42.59
	2.5	0.72	0.96	33.19
	3	0.99	1.23	24.01
Torque Ripple (%)	0.5	112.08	86.21	-23.08
	1	70.07	61.59	-12.11
	1.5	61.34	57.79	-5.79
	2	58.97	57.30	-2.85
	2.5	58.43	65.19	11.57
	3	63.48	74.85	17.92

III. POWER CONVERTERS

SRMs inherently suffer from torque ripple, and in high speeds mutual coupling of phases take place. These issues can be addressed by accurate commutation, and current control and smooth phase switching. Since SRM does not have homogeneous rotating airgap field, nonconventional power converters are needed. For SRM drives, the torque produced of the direction of excitation current, they can work with as little as one switch per phase. Once, commutated sizeable magnetic energy must be dissipated, to protect the phase windings and the semiconductor switches from excess voltage.

The power converter for SRMs has the advantage of having a low number of switches and semiconductor diodes that reduces the number of control and gating circuitry. An asymmetrical H-bridge is the most widely used topology in SRM drives. A study was done by Vukosavic et al. in 1991 compares asymmetrical H-bridge, Miller circuit, buck-boost inverter, C-dump inverter, and the Sood's inverter. The results indicate that the classical asymmetrical H-bridge inverter is the most viable topology for SRMs, with a current overlap over most of the speed ranges [30]. Modifications of these topologies have also been developed to improve switching performance, increase the rate of demagnetisation, allow phase overlap, regenerative braking.

Most often, the choice of power converter topology depends on the application for which the drive is being used. For example, in non-critical, low-performance applications like door actuation system, forklifts, and such applications do not require high-performance drive and inexpensive power converters can be used. In aerospace and EV applications, and high-performance is top priority and thus requires efficient power converters with smooth commutations and fail-safe redundancies. These applications also require accurate control strategies to ensure smooth operations. The most significant features of SRM power converters can be listed as:

- Independent conduction of each phase, i.e., at least one switch for each phase.
- The phase must be demagnetised fully before getting into regeneration mode to avoid negative torque.
- High reliability because switches are always in series with the phase and in parallel to the source.
- Safe operation in case of phase failure.

Table II compares various commonly used topologies used for SRM drives.

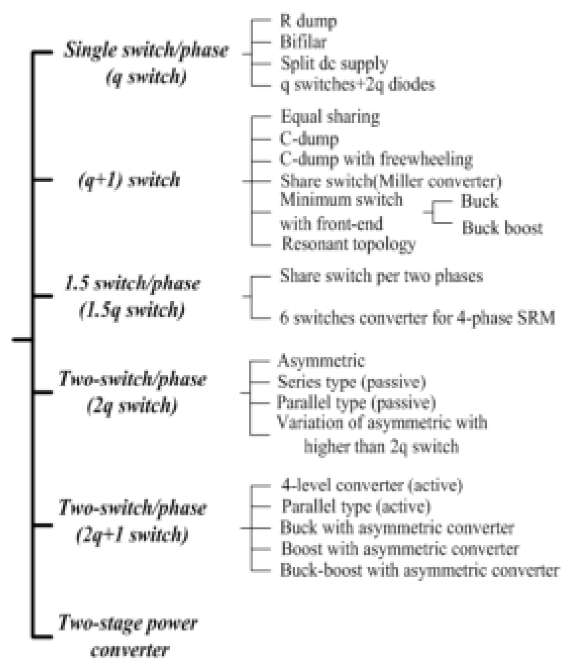

Fig. 3: Classification of power converters for SRM applications. [35]

In a paper presented by Azer et al. [34] a three-level T-type converter was proposed for SRM drives in HEVs. Its operation is compared to conventional asymmetric NPC converter. This novel design is proposed to replace asymmetric NPC converters in EV/HEV applications. The results show the proposed converter has better efficiency and reliability against open-switch faults while having comparable costs. Simulation results show that the proposed converter outperforms the conventional converter by 10%.

TABLE II. COMPARISON OF COMMONLY USED CONVERTERS FOR SRM [19]

Converter type	Benefits	Drawbacks	Applications
R-Dump Converter	Low Cost	Low efficacy	Low speed
C-Dump Converter	Independence phase control	Low efficiency	Low speed
C-Dump with Freewheeling	Low cost	Complex control	Motoring operation
Asymmetric, Series& Parallel	High efficiency, Simple control	High No. of devices	Low power
Bifilar	Regenerative operation	Low power density	Small motors
Split DC supply	Low cost	Motoring operation only.	Even phases No. motors
Minimum Switch with Variable DC- link	Low core losses, Reduce noise, Low switching	Low efficacy	Sensorless applications
Two- Stage Power Converter	High power density	High No. of devices	Wind energy
Resonant Converter	Low switching losses, High switching	Low power density EMI influence	High-frequency applications

IV. CONTROL STRATEGIES

Despite several advantages, the SRM has certain key disadvantages, namely, acoustic noise, vibrations and torque ripple. Although the drivers for SRMs can be as simple as asymmetric full-bridge converter, they require sophisticated control strategies. Especially for high-performance EVs simple PID controllers do not suffice, and they require complicated algorithms running at high speeds on modern DSP chips. In recent times, several modern control strategies for machines have been presented, like model-referencing adaptive control, self-tunic control, fuzzy control, neural network control, AI-based control, etc. For high-performance EV propulsion systems, fuzzy control and neural network control have been proven to be promising [15]. To implement sophisticated controllers, high-speed modern microelectronics, microcontrollers and microprocessors are essential. Commonly used microcontrollers are DSP chips which utilise high-speed variable-point computation to determine the control output. In specific high-end applications, transputers, which are intended for parallel computing, are also used.

The control of SRMs is achieved by using two different methods, with a position sensor or without a position sensor. In the latter, the position of the rotor is estimated using various parameters. In sensor-less methods, at least one current sensor is needed to detect the DC link current and rotor position. The SRM control can be done based on performance requirements such as minimising torque ripples or accurate speed and torque response [20]. This is achieved by three main control strategies: current control, speed control, or torque control, a brief survey of these techniques are presented here.

A. *Current Control:*

The SRM can be controlled using both voltage and current controllers. The voltage controller has lesser implementation costs but tends to be prone to voltage ripple on the supply side, so it is essential to use current control techniques for accurate torque control of SRM. The current control can be subdivided into two categories, i.e., Hysteresis Current Control (HCC), also known as Current Chopping Control (CCC) and Pulse Width Modulation (PWM) control [16][17]. HCC is a basic strategy used in low-speeds or during starting. In this control, the phase current is compared to some pre-set reference value, and a hysteresis band is determined between maximum and minimum current around the reference. During starting the phase current rises sharply, and HCC can be used to limit the peak current [18]. The HCC has been used for current control with simple switching but requires high switching frequency to reduce the current ripple. The most significant advantage of this type of control is that it can be implemented very easily using simple analogue circuits and is very robust.

In PWM control, linear controllers like P, PI, PID and such can be implemented and run quite cheaply, especially in lower-end drives. In this control, the difference between a set point and the control input is fed to the controller, and the control output is used to determine the duty cycle. When the motor runs at a speed controller cannot track, the switch is kept ON continuously till commutation occurs. This is called Single Pulse Control (SPC). PWM control can easily be implemented using both high-end digital controllers and simple analogue electronics [19].

B. Speed Control:

In speed control, the feedback signal is measured using a speed sensor or rotor position sensor and is compared to a reference speed. In EV applications, the reference speed is set from the throttle input. The speed controller adjusts the speed according to reference and gates the power switches according to the speed to obtain higher efficiency and better performance, especially in high-performance drives. It is common to use a double loop speed control strategy in high-performance drives. Throttle sets the reference current of the outer current loop, and its outputs act as reference for the inner speed control loop. Parasivam et al. [20], have proposed an advanced DSP based controller based on linear controllers, and the controllers have been experimentally shown to accurately control speed over a wide range and at various conditions.

C. Torque Control

In SRMs there exists a three-dimensional relationship between flux linkages, excitation currents and rotor positions, which leads to a nonlinear relationship between the torque and excitation current [20]. There are two broad types of torque control, i.e., indirect torque control, which uses complex algorithms to determine the reference current, and direct control which uses more straightforward methods like torque hysteresis control to reduce the torque ripple [19].

A simple, powerful and reliable method of indirect torque control is by using Torque Sharing Function (TSF). In this method, the rotor position is sensed, and the torque requirement reference is determined. The reference torque is then split for each phase and accordingly reference phase currents are determined. Each phase current is compared with reference values, and linear or nonlinear controllers then generate the gating signals for the power converters. TSF can be optimised for minimum torque ripple using intelligent systems like genetic algorithm and neural networks. Although, simple to implement, most of indirect methods require several predetermined values such as command current and switching angle, and they must be determined offline or experimentally. The generated values are kept in lookup tables and are reference according the input signal and operating conditions. Experimentally determining several control values can be expensive, especially for higher-end controllers.

The drawbacks of indirect torque control can be overcome by using direct torque control, which in recent years have been proven experimentally. In the direct torque control method, the motor torque itself is the control variable. SRMs have nonlinear relationship between torque and excitation current, so it is not possible to determine the instantaneous torque using straightforward machine equations. Instantaneous torque can be estimated in two ways that are, torque as a function of phase currents and rotor position, or torque as a function of flux linkage and phase currents. These relations can be easily determined using both experiments and by using FEA. The rotor position and phase currents can be used as control input, and these inputs are compared with torque response curves to determine the torque reference which is stored as lookup tables. A digital hysteresis controller can be used to generate the switching signals for the power converters. Direct instantaneous torque control is considered to be one of the most promising control strategies for high-performance drives primarily due to simple and less number of control variable, smooth torque quality, accurate steady-state torque control at low speeds and inherent compensation of torque ripple over phase commutation. A PWM generator can be implemented with the traditional direct instantaneous torque control to control the duty cycle of the power switches, called advanced direct instantaneous torque control. By using this strategy, the phase voltages can be regulated to control the currents in single sampling time. Another method to improve the performance is by predicting the future states of the system to obtain the optimum switching commands. The predicted states lead to the desired value of output torque. Carefully modelling techniques must be used to develop accurate machine models and get the machine data. The only state variables here are the rotor position and flux linkage. It is worthwhile to note here that no current loop exists in this strategy and the current is used to determine the flux linkage. The benefit of the strategy is the ability to reduce the bandwidth of the control; consequently, can be easily be implemented using DSP chips.

Acoustic noise and vibrations remain one of the biggest challenges that the research in SRM needs to be overcome. The main culprit which causes vibrations is the pulsating forces, specifically radial forces, experienced by the rotor due to the excited stator and the neighbouring stators [21]. Recently, for SRMs with high number of poles a basic idea to eliminate noise and vibration by flattening the radial forces sum has been investigated. A simplified current waveform has been proposed to reduce the vibrations.[22]-[26].

V. AUTOMOTIVE APPLICATIONS

In early designs for SRMs for applications, the efficiency of the drives was prioritised, and only later the designs were optimised for EV and HEV applications [27]. While designing an SRM for EV/HEV application, special attention is to be given to the vehicle dynamics. Propulsion systems for EVs require a special speed-torque characteristic which is dictated by the vehicle dynamics. Studies have shown that the powertrain must work entirely in constant power region, to meet the operational characteristics like gradability with minimum power and initial acceleration [28]. A motor working in constant power region will have a power rating half of the motor working that deviates from the constant power region. Operation entire in constant power region,

TABLE III: COMPARISON OF SRM DESIGNED FOR EV/HEV POWERTRAIN. [30]

Affiliation	Peak power	Peak torque	Maximum Speed	Maximum speed at peak torque	Maximum power-to-weight ratio	Efficiency over 85% region portion	Machine topology	Cooling method	Validation method
University Manchester	26 kW	120 Nm	4,500 rpm	1,200 rpm	N/A	N/A	24/16	Liquid/Coolant	Experiment
Fukuoka Inst of Tech	30 kW	594 Nm	2,200 rpm	482 rpm	N/A	N/A	6/4	Liquid/Water	Simulation
Meiji University	40 kW	100 Nm	6,400 rpm	3,000 rpm	N/A	N/A	12/8	N/A	Experiment
University of Akron	50 kW	122 Nm	12,000 rpm	8,000 rpm (48 Nm)	N/A	60%	12/8	Liquid/Water	Experiment
Illinois Inst of Tech	50 kW	300 Nm	6,000 rpm	1,600 rpm	1.18 kW/kg	85%	12/8	N/A	Simulation
General Motors	56 kW	710 Nm	N/A	750 rpm	N/A	70%	24/16	Liquid/Coolant	Experiment
McMaster University	60 kW	210 Nm	13,500 rpm	2,750 rpm	2.64 kW/kg	92%	24/16	N/A	Simulation
Newcastle University	82 kW	285.8 Nm	10,500 rpm	2,750 rpm	2.52 kW/kg	N/A	12/8	N/A	Experiment
Toyota Industries	100 kW	164.7 Nm	10,000 rpm	5,800 rpm	2.22 kW/kg	N/A	6/4	Liquid/Oil	Simulation
HUST	101 kW	377.3 Nm	4,500 rpm	2,556 rpm	0.94 kW/kg	80%	8/6	Liquid/Coolant	Experiment
Tokyo Inst of Tech	109 kW	209 Nm	13,900 rpm	5,400 rpm (185 Nm)	4.32 kW/kg	88%	18/12	Natural Air	Experiment

however, is not possible for any practical drive. Although operation in an extended constant power region is possible if the motor is designed appropriately and is controlled properly [29]. A comprehensive list of SRMs developed by various academic institutes is shown in TABLE, and the critical EV motor performance characteristics are presented.

Most of the ongoing research on SRMs are targeted to design and manufacture SRMs comparable to commercially available EV/HEV drives, such as Nissan Leaf and Toyota Prius [30]. In a study presented by Kasprzak et al. [31] and Jiang et al. [32] a 24/16 SRM with same stator outer diameter and axial length was proposed, and with a torque-speed curve compared to the Prius motor. The proposed machine also has a better efficiency owing to thinner laminations to compensate for higher iron losses at higher speed. The pulsed nature of stator excitation leads to considerable torque ripple; thus most of the SRM designs use a three-phase or four-phase excitation to reduce the torque ripple. With proper control strategies, all motors can generate maximum torque at a standstill. A sizeable maximum speed at peak torque is also a preferred advantage, indicating the maximum acceleration the motor can provide while running at moderate speed. It is important to note here that conventional ICE also has significant torque ripple [33], and since the EV/HEV propulsion systems work at dynamic states, torque ripple may not be a significant problem. In addition, torque ripple can be reduced by using advanced control strategies.

VI. CONCLUSION

This paper presents a brief review of the emerging technology of switched reluctance motor and drives for EV/HEV applications. Existing methods for designing and modelling of SRM is discussed, and novel design to improve performance is presented. Various converter topologies used in SRM drives for EV/HEV is presented and compared. Commonly used control strategies for speed, current and torque control is presented, and novel strategy to reduce torque ripple is presented. A brief research overview of SRM in automotive applications is also presented to serve as a summary for future work is presented. This paper is meant to serve as brief beginning guide towards developing new SRM technologies.

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