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Permanent Magnet Motors and Switched Reluctance Motors Capabilities for EVs and HEVs: A Comparative Analysis

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Abstract: *This paper presents a comparative analysis of the capabilities of permanent magnet motors and switched reluctance motors (SRM) for use in electric vehicles (EVs) and hybrid electric vehicles (HEVs). With the increasing pollution caused by conventional vehicles, electric motors are becoming increasingly popular as a means of reducing environmental impact. High power density magnetic motors such as brushless DC (BLDC) motors and permanent magnet synchronous motors (PMSM) have been the preferred choice for EVs and HEVs. However, they face challenges such as demagnetization, high cost, and fault tolerance. As a result, SRMs are expected to replace permanent magnet motors in the future for EVs and HEVs, as they have no permanent magnets on the rotor, offer a higher torque-to-power ratio, lower losses, and lower acoustic noise compared to BLDC motors and PMSMs. This paper analyzes the performance characteristics, power density control, torque ripple control, vibration control, noise, and efficiency of these special electric motors. It also offers a review of the unique aspects of BLDC motors, PMSMs, and SRM-based drive systems for EVs and HEVs, while explaining why permanent magnet motors are being replaced with SRMs for use in EVs and HEVs.*

Keywords*: Brushless DC (BLDC) Motors, Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs), Power Electronics Converters (PEC), Permanent Magnet Synchronous Motors (PMSM), Switched Reluctance Motors (SRM) and Special Electric Motors (SEM).*

I. INTRODUCTION

Currently, conventional vehicles emit harmful air pollutants during their operation, such as sulfur dioxide, hydrocarbons, carbon monoxide, greenhouse gases, and nitrogen oxides. To address this issue, researchers are focusing on developing electric vehicles (EVs) and hybrid electric vehicles (HEVs) to minimize the production of these gases in the environment. As a result, there is a growing trend of people shifting towards EVs and HEVs, which are powered by special electric motors (SEM).

Permanent magnet (PM) machines are suitable for electric vehicles (EVs) and hybrid electric vehicles (HEVs) due to their benefits. However, the limited and expensive resources of PM materials have led to increasing attention on PM-free electric motors such as switched reluctance motors (SRM) [1]. SRMs are considered physically powerful candidates for EVs and HEVs due to their strong construction and low cost [2]. SEMs are gaining popularity in the EVs and HEVs market due to their high-power density control, torque to inertia ratio control, speed range, and reliability. Currently, permanent magnet synchronous motors (PMSM) and brushless DC (BLDC) motors are being used in electric vehicles, but these motors require permanent magnet material for torque production. Therefore, new technologies such as SRMs have been introduced and demanded for rare-earth-free motors. SRMs are recognized for their simpler and stronger construction without any windings and permanent magnets on the rotor [3].

The SRM has numerous advantages over BLDC and PMSM motors, including longer lifespan in harsh environments and more cost-effective motor drive operations [3]-[4]. It also provides excellent efficiency, reliability, and starting torque during acceleration, as well as strong fault tolerance. To improve the SRM's structure, reliability, and control techniques, position sensor-less control techniques [4]-[5] and fault acceptance techniques [6]-[7] have been developed for safety-critical applications. The main factors for selecting motors in EVs and HEVs are cost, weight, and efficiency [8].

Large motors can increase the weight of the overall system, leading to lower acceleration and reduced vehicle performance. Therefore, special electric motors are the optimal choice for EVs and HEVs as they are relatively inexpensive, robust, and lightweight [9].

With the advancements in power electronics and control systems, there is a need for superior electric motors that can meet the required performance indices of EVs and HEVs at a lower cost [10]. The desired specifications for an ideal EVs and HEVs include higher efficiency, power density control, specific torque, lower noise, constant power, speed range, dynamic response, ruggedness, robustness, and cost [11]-[12]. The objective of this study is to provide a comparative analysis of permanent magnet motors and SRMs for their suitability in EVs and HEVs. The drawbacks of permanent magnet motors and the major advantages of SRMs are explained in detail. Finally, the three types of motors are compared in the context of EVs and HEVs.

The following is the paper's structure: In Section II, we will cover the various types of electric vehicles, while Section III will focus on electric motors for EVs and HEVs. Section IV will discuss power electronics and control systems for SRM drives, and Section V will examine challenges and opportunities in the power sector. Finally, in Section VI, we will provide concluding remarks for the paper.

II.TYPES OF ELECTRIC VEHICLES

Electric energy is typically stored in hydrogen powered fuel cells, batteries, and super capacitors. Currently, EVs and HEVs use various types of electric motors such as SRM, PMSM, BLDC, and induction motors (IM). In HEVs, the motor acts as a generator and generates electrical power that can be stored and utilized later. Electric motors in EVs and HEVs are connected to internal combustion engines (ICE) through series or parallel connections. Power electronic semiconductor switches like BJT, MOSFET, and IGBT are used in control systems, along with various types of control techniques such as linear and non-linear controllers implemented on different control platforms like DSP and microcontrollers.

The main difference between HEVs and ICE vehicles lies in a) the system that converts electrical power into mechanical torque on the wheels, b) the system that stores electrical energy, c) the modified ICE system used in HEVs, and d) the transmission system that facilitates the connection between different control techniques. The main goal is to use renewable energy sources (RES) in EVs and HEVs applications to improve system efficiency.

A.Plug-in Electric Vehicles

Fig. 1 depicts the basic components of plug-in electric vehicles, which include the battery, power electronic converter, motor, and gear system. The energy stored in the battery is converted into AC depending on the driving system used by the vehicle. One of the primary benefits of plug-in electric vehicles is that they are pollution-free and environmentally friendly. However, a major drawback of these vehicles is the quick depletion of battery charge, which limits their use for long-distance travel applications.

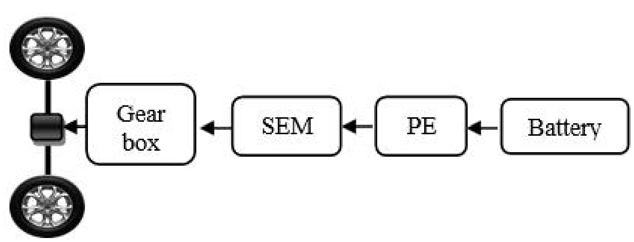

Fig. 1. Plug-in electric vehicles.

B. Hybrid Electric Vehicles

HEVs are vehicles that utilize a combination of electric and other energy systems to power the vehicle. These vehicles typically consist of an electric drive system, various types of motor supplies, and additional power sources like internal combustion engines to drive the vehicle. Major car companies like Toyota and Honda have already begun producing HEVs, which have become increasingly popular among consumers due to their high mileage and reduced pollution.

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III. ELECTRIC MOTORS FOR ELECTRIC AND HYBRID ELECTRIC VEHICLES

Figure 2 displays the configuration of various electrical motors utilized in EVs and HEVs. Each motor type has its own advantages and disadvantages, which make them suitable for various hybrid vehicle concepts. Figure 3 illustrates the schematic layout of electric and hybrid electric vehicles, which consist of power electronics components, batteries, and control logic.

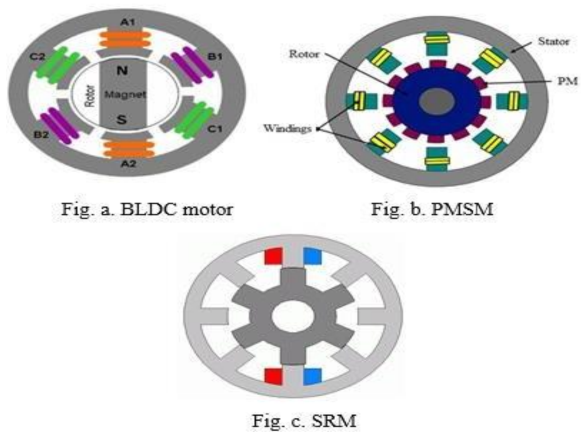

Fig. 2. Basic stator and rotor configurations: (a) BLDC motor, (b) PMSMand (c) SRM.

A.BLDC motor and PMSM

PMSM and BLDC motors require PM in the rotor part to generate the required excitation. The high energy density of the PM provides advantages such as requiring less space. At nominal speed, both motors achieve high efficiency due to zero excitation current. However, iron losses are significant in PMSM and BLDC motors, which can be dissipated with the use of case cooling system. Nevertheless, the cost of the magnet is high, and field weakening is necessary in the BLDC motor and PMSM, which can increase stator loss and decrease efficiency at high speeds. Additionally, magnetic characteristics limit the overload capacities of BLDC motor and PMSM.

The torque speed curve of PMSM utilized in EVs is depicted in Fig. 4. The constant torque, constant power, and high-speed regions are represented in the graph, with various ranges of speed and torque variation. In the PMSM's constant torque region, the rated speed is not achieved, and a constant torque is produced. As the speed approaches the rated motor speed, the torque decreases proportionally, leading to constant output power. When the speed is further increased, the constant power section comes to an end. Additionally, the motor torque decreases proportionally to the square of the speed.

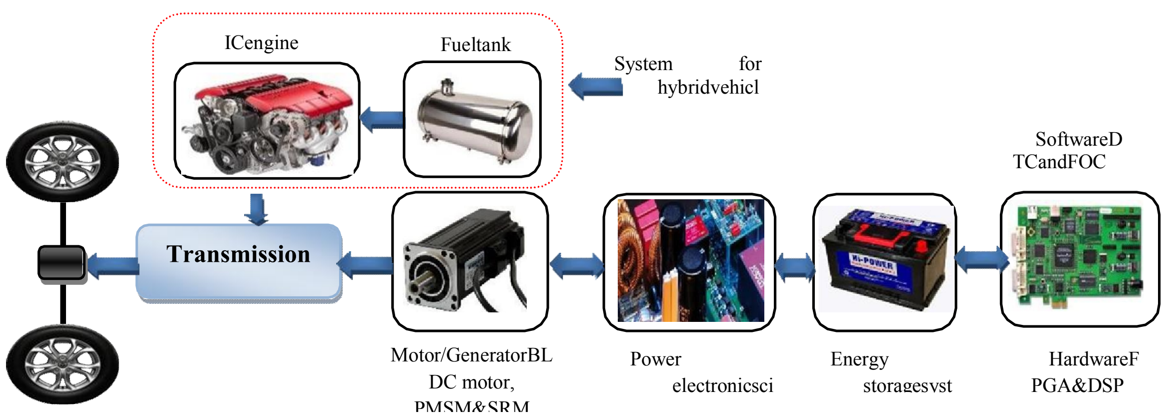

Fig. 3. Schematic layout of electric and hybrid electric vehicles

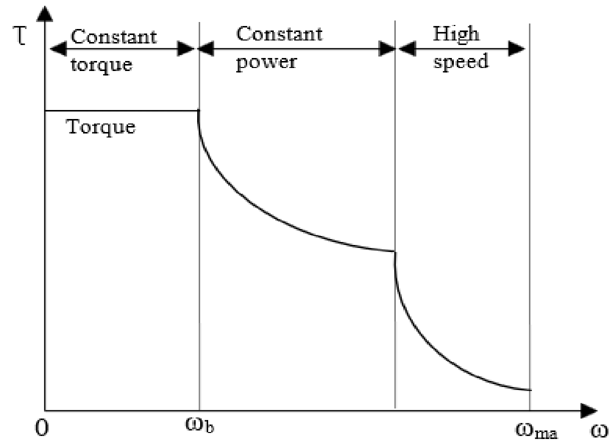

Fig. 4. Torque speed characteristics of PMSM

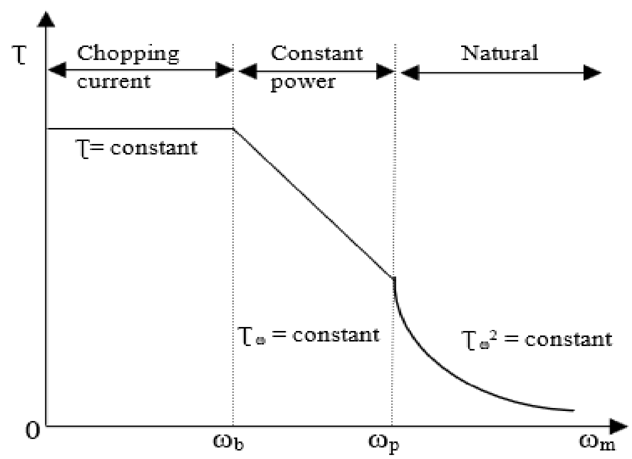

Fig. 5. Torque speed characteristic of SRM.

B.SRM

The principle of SRM has been understood for a long time, but it has not been widely applied in power electronic applications until recently. Compared to conventional motors, SRM offers improved power density and efficiency. The construction of SRM is simple, with a concentrated stator winding and no rotor winding, leading to better performance. However, the non-linear nature of current switching angle identification makes controlling SRM more difficult than other three-phase machines. The torque speed characteristics of SRM are depicted in Fig. 5, where the current in the stator winding is switched ON and OFF based on the rotor position. The natural region refers to the one with constant frequency and constant switching angles. Here, ωb denotes the base speed, which is defined as the speed at which peak current can be delivered to the motor rated voltage with constant switching angle.

Fig. 6 illustrates the coordination of the battery and IC engines at different speeds. Depending on the speed variations, the battery and IC engine can either work together or work separately to achieve better starting and steady-state performance. The base speed (ωb) is the maximum speed at which the motor can receive the maximum current (Imax) at rated voltage with fixed switching angles.

At a specified speed the flux is directly proportional to the voltage V, and the torque differs with the current squared. Thechopping voltage control is intelligent to control an SRM drive only in the mode under rated speed where the generated voltage, being greater than the back-EMF, forces the drive states on the sliding surface [3]. If fixed switching angles are continued at speeds above ωb, the torque falls as 1/ω. This is the second significant mode of operation, when the machine speed is beyond the base speed (ωb).

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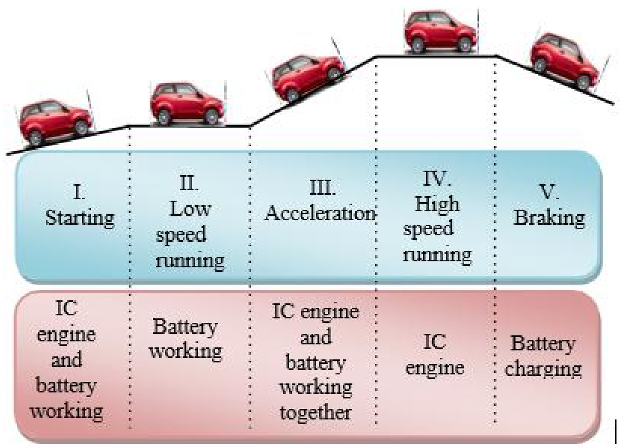

Fig. 6. Coordination of the IC engine and the battery working in different speed conditions.

The battery and IC engine of vehicles operate in different speed regions depending on the variation in speed. They can sometimes work together or separately to improve starting, acceleration, and steady-state performance. In order to enhance torque efficiency, multilevel voltage, fast excitation, and fast demagnetization are used in both IC engine and battery driving modes. Table I and Table II illustrate the advantages and disadvantages of electric vehicles and the comparison between permanent magnet motors and switched reluctance motors, respectively.

TABLE IADVANTAGES AND DISADVANTAGES OF ELECTRIC VEHICLES

Sr.No.	Advantages	Disadvantages
1	No gas required	Charging points
2	No emission	Electricity is not free
3	Safe to drive	A short driving range and speed
4	Cost effective	Not suitable for cities facing shortage of power
5	Low maintenance	Safety and security problems
6	Reduce noise pollution	High starting cost

According to Table II, switched reluctance motor drives are the most promising contenders for EVs and HEVs applications. Higher numbers in the table indicate better performance. After careful analysis, a SRM was chosen due to its simple construction, robustness, and suitability for mass production of motor drives for electric vehicles.

TABLE II.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**

IV.POWER ELECTRONICS AND CONTROL SYSTEM FOR SRM DRIVE

The SRM is a voltage source inverter based rotating machine in which controller and drive system is essentially required for the operation. The controller includes, drive mechanism, PEC and also with different types of sensors for sense the mechanical and electrical signals (phase current, phase voltage, rotor position and torque).

A. Converter Selection

The torque of the SRM system is completely independent of the excitation phase current polarity, making it advantageous for driving the motor system with various circuit topologies. Fig. 7 illustrates the asymmetric bridge type inverter for per phase SRM drive. By connecting diodes D1 and D2 in parallel with switches S1 and S2, a semiconductor switch with bidirectional capability is achieved. A comprehensive review of power electronic converters used for SRM application is presented in [19]. In the asymmetric bridge type inverter, two switches are turned on simultaneously to magnetize the phase, which converts electrical power into torque.

B. Control of SRM

The PI controller is widely used in industry for the speed control of SRM. The desired torque is converted into electrical references for the motor using a method that depends on the system configuration and motor type. The phase currents in the SRM motor are determined based on the expected torque. The phase currents are regulated using the PWM method up to conventional speed, which is one of the basic control systems used in SRM. However, during high speed, the dynamic characteristics of motor currents make it difficult to control the phase currents using these methods. In real-time applications, such methods are not used. The control-based system of SRM faces a significant challenge in noise control, and more research needs to be done in this area.

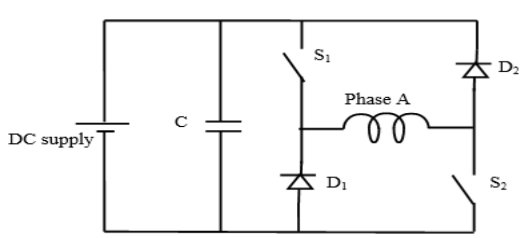

Fig. 7. Asymmetric bridge converter for one phase of an SRM

C. Sensorless Control of SRM

In order to operate an SRM-based drive system in EVs and HEVs, it is necessary to determine the rotor position in sequence. While using sensors for position sensing, more precise phase details are required when the number of phases in the SRM-based drive system is increased. However, sensor less control is considered more effective than sensor-based control systems. Sensor-based control systems have higher initial costs and installation is also more complex. The speed-torque characteristics of a SRM drive can be classified into low-speed area, high-speed area, ultra-high-speed area, constant torque area, and standstill condition. Detailed information about various estimation techniques is discussed in [23]. Different types of estimation techniques have been proposed for each speed range and combined methods may also be utilized for achieving additional benefits.

V.CHALLENGES AND OPPORTUNITIES FOR THE POWER SECTOR

To ensure satisfactory service quality, the electrical system plays a crucial role in the development of EVs. Circuit topologies, control techniques, and charging methods are key factors that determine the progress of this field. EVs can be charged at different locations such as homes and public charging stations, and hence, improving efficiency, ensuring safety, and integrating software tools can help reduce the cost of circuit components and the weight of energy storage elements. These are urgent requirements for the development of EVs and HEVs [24]-[25].

VI.CONCLUSIONS

Several electric motors were compared to determine the most suitable for electric vehicles (EVs) and hybrid electric vehicles (HEVs). The comparison focused on their power density, efficiency, advantages and disadvantages, and applicability in EVs and HEVs. Among the compared motors, the switched reluctance motor (SRM) stood out due to its simple construction, low cost, robust design, and fault tolerance. The SRM combines the benefits of brushless DC (BLDC) motors and permanent magnet synchronous motors (PMSM) while significantly improving its power density, torque, vibration, and acoustic noise, making it a superior choice for EVs and HEVs applications. A comprehensive comparative study demonstrated that SRM surpassed BLDC motors and PMSM in torque-to-power performance. Based on this study, it was concluded that SRM is the most suitable motor for EVs and HEVs applications.

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