

Review of Electrical Motor Drives for Electric Vehicle Applications

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ABSTRACT

EVs (Electric Vehicles) have been rejuvenated over the last decades while the motor drive technologies are still evolving. This paper provides a review of electrical motor drive technologies used in EV applications, with a performance comparison of candidate machines and their drive topologies. EV applications demand high efficiency, high torque density, high reliability, and wide speed range while reducing weight, complexity, total costs and environmental impact. In the literature, DC (Direct Current) motors, IMs (Induction Motors) and PM (Permanent Magnet) motors can be generally found in marketplace whilst RMs (Reluctance Motors) have been researched for some time and are nearing commercial availability. This paper evaluates the performance of these four main types of electrical motor drives for EV propulsion applications using analytical methods. PM motors may offer the best performance in terms of torque density and compactness but the cost is the highest (primarily dominated by rare-earth permanent magnets), limiting their widespread application in mass production EVs. DC motors have their own merits but suffer from limited power density and necessity for maintenance. Induction motor drives are a mature and proven technology. In particular, squirrel-cage IMs are robust, reliable and inexpensive, striking a balance between system cost and complexity, power density and extended speed range. Reluctance motors can provide a good torque density and cost effective EV drive solutions. Their drawbacks can also be overcome by the use of power electronic converters and advanced control strategies. Induction and reluctance motor drives are well suited for cost sensitive mass production EV applications. Looking to the future, increased hybridization may be a way forward in industry which combines attractive features of different electrical machines and control algorithms and still offer much promise in performance and total cost. At last, reliability study on EVs requires historical information and driving patterns, demanding research expertise in eco-sociology, human behaviors as well as human-machine interface.

Key Words: Brushless PM Motors, DC Motors, Electric Vehicles, Fault Tolerance, Motor Drives, Reliability, Squirrel Cage Induction Motors, Switched Reluctance Machines, Variable Speed Drives.

1. INTRODUCTION

There is a rapid development in transportation industry to move toward EVs, which are considered to be highly efficient and reliable, and are now becoming commercially competitive. EVs

include HEVs (Hybrid Electric Vehicles), PHEVs (Plug-in Hybrid Electric Vehicles), more MEVs and all AEVs, depending on the electrification level of the vehicle.

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In order to meet the increasing demand for EVs, substantial investment from governmental sectors, research institutions, industry and public have been directing into research and development, production and commercialization activities of EVs. EVs have a very broad range of specifications. Each application places different demands on the motor and hence many different technologies are appropriate. In urban areas, passenger vehicles have been the major source of air pollution [1-3] and therefore the focus of this paper.

2. HISTORICAL DEVELOPMENT OF ELECTRIC VEHICLES

It may be surprising to know that the EV is a far cry from exciting new concept. Earliest models can be dated back to 1820s just after electromagnetism was first discovered. The first small electric car was completed in 1835 that was still 50 years earlier than the appearance of an ICE (Internal Combustion Engine) car. Early waves of the land travelling speed records were all set by electric motors-propelled vehicles. Nonetheless, owing to limited availability of electricity and batteries, and absence of charging stations, these EVs were in limited use in cities.

With the advent of the first practical rechargeable battery lead-acid accumulator during the era in 1859-1960 [4-5], EVs started to gain in their popularity. The commercially successful electric cars first appeared in France in 1893 and then in the US in 1896. Around 1900-1910, electric cars reached the height of their success primarily due to their odorless and quiet features [6], rechargeable batteries, and importantly, reliable DC motor drives. However, they were expensive, low ranging and limited by the low power density of batteries. The typical achievable range in 1900s was around 40-100 miles on a charge, as compared to 244 miles for today's Tesla [7-8]. It was the ICE technology that ended the EV's dominance

in passenger vehicles. First built in 1885 [6], the ICE vehicles soon became mature and commercially successful with an aid of availability of cheap gasoline and service stations. EVs slowly went extinct from the market since the early 20th century.

However, over the last three decades, concerns about climate change and the depletion of oil reserves have continued to grow. Given the fact that fossil fuel-based transportation plays a key part in emitting greenhouse gases, decarbonization of transportation industry has led to a renewed interest in EVs.

EVs can provide stop-and-go and regenerative braking capacities, potentially reducing the fuel consumption by up to 10% [9]. Without a doubt, EVs can improve air quality and petroleum conservation while offering tremendous environmental, societal and economic benefits. Typical specifications of an electric car are given in Table 1.

The major requirements of EVs' propulsion drives are summarized as follows [10-12]:

- High instant power and high power density
- High torque at low speeds for starting and climbing, and high power at high speed for cruising

TABLE 1. SPECIFICATIONS OF AN ELECTRIC CAR

Parameter	Value
Top speed (flat road)	120 km/h
Acceleration (0-50 Km/h)	9 sec
Curb weight	550 kg
Payload (3 persons + 40 kg)	250 kg
Full load weight	800 kg
Frontal area	1.5 m ²
Aerodynamic drag coefficient	0.35
Wheel rolling radius	0.3 m
Over speed factor	1.2

- Very wide speed range including constant-torque and constant-power regions
- Fast torque response
- High efficiency over wide speed and torque ranges
- Regenerative braking capacity
- High reliability and robustness for various vehicle operating conditions
- High fault-tolerance
- Power converter technology
- Low total cost.

3. TYPES OF ELECTRICAL MOTOR DRIVES

EM drives as propulsion are at the heart of EVs. They need to operate in a harsh environment with the humidity of up to 85% and the ambient temperature between -40 and 135 celsius degree. This is particularly true for HEVs where EMs are in proximity to the ICE. Other specifications include high driving duty cycle, wide constant-power range and high torque density.

These requirements for EV drives can be depicted in Fig. 1 [9] and should be matched by the output characteristics of an EM drive. Typically, an EV motor needs to generate a peak torque (during starting, acceleration or hill climbing) which is 5-10 times the torque for cruising [13-15]. In Fig. 1, the constant power region represents high speed cruising where the maximum speed may be five times more than the base speed. Gearbox costs indicate a maximum motor speed around 10,000 rpm.

As reported in literature, DC motors, IMs and PM motors have been widely used in EV propulsion drives while RMs have begun to emerge in the automotive market. The feasible machines are illustrated in Fig. 2 and their cross-sections are shown in Fig. 3(a-d) [16] for comparison. The features of each candidate motor drive are further described as follows:

DC Motors: The earliest EVs used almost exclusively DC motor drives [4] simply because the DC supply was available from the battery in vehicles. This covered the period when DC machine technologies were developed and gradually perfected.

As shown in Fig. 3(a), the magnetic field in DC motors is established by the PMs (or electro-magnets) on the

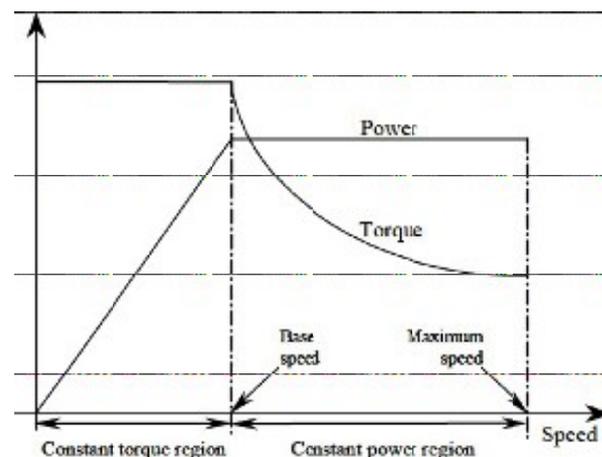


FIG. 1. REQUIRED CHARACTERISTICS FOR EV MOTOR DRIVES [9]

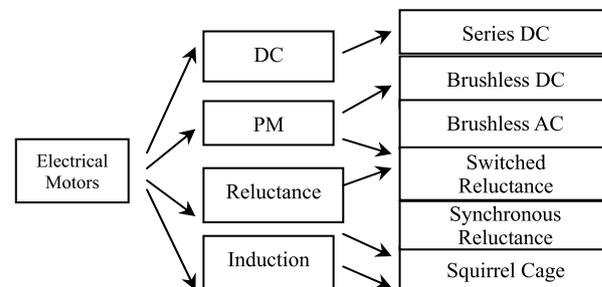
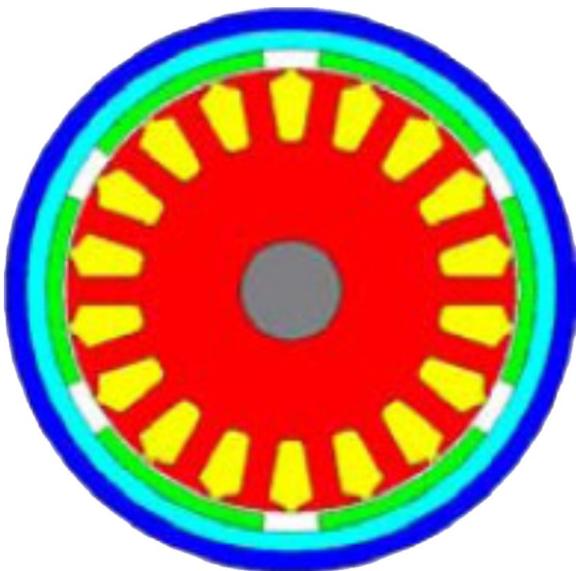


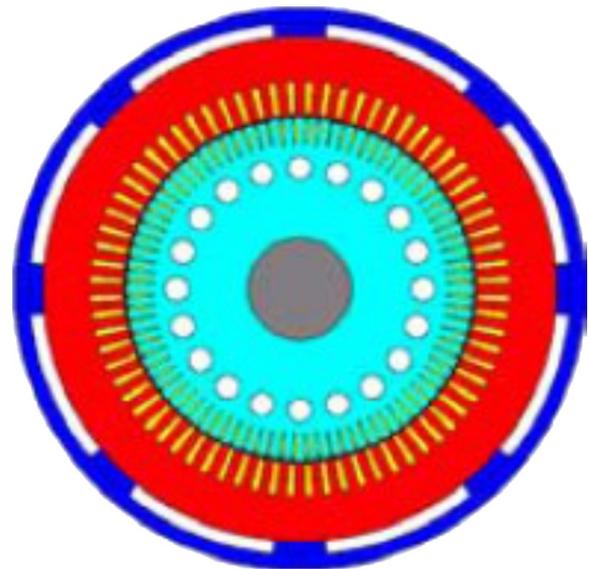
FIG. 2. MACHINE OPTIONS FOR THE EV PROPULSION APPLICATIONS

stator and the armature is wound on the rotor. In DC motor drives, speed and torque control is simple, independent, and their torque-speed characteristics suit for EV propulsion drive. Especially, the series DC motors are very appealing an option. They connect the field and the armature circuit in series and have a unique torque-speed characteristic to provide high torque at

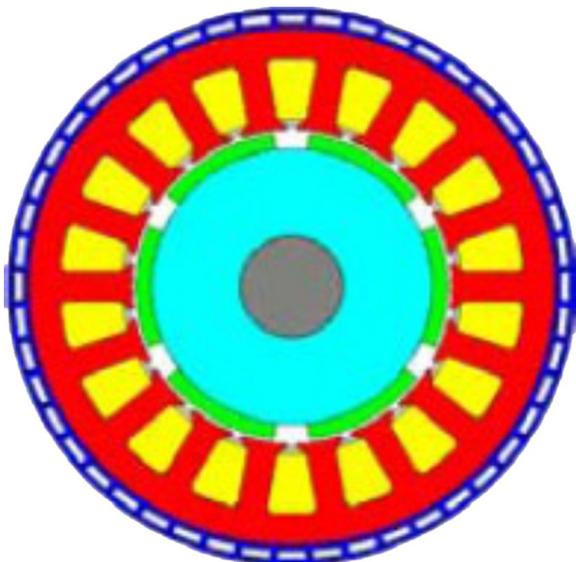
low speeds and low torque at high speeds. Furthermore, they do not require a separate excitation source. When overloaded, the demagnetization effect of armature reaction is balanced by the field strengthening. These in combination make the series DC motors the prominent technology for electrified transportation applications until 1980s [13-15].



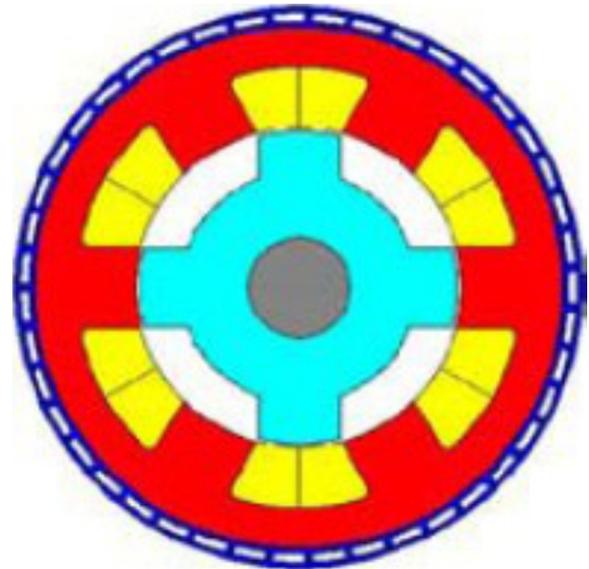
(a) DC MOTOR



(b) INDUCTION MOTOR



(c) PM MOTOR



(b) RELUCTANCE MOTOR

FIG. 3. ELECTRICAL MACHINES FOR EV PROPULSION DRIVES [16]

However, they are large, lossy and inefficient. Further, disadvantages of DC motor drives are primarily associated with the usage of commutators and brushes, which add maintenance requirements and costs. Moreover, they have a limited regenerative braking capacity. When field weakening is achieved by using power electronic diverters to shunt a portion of the armature current [13], motor efficiency would be compromised. Ultimately, their ac counterparts are more successful with the help of advanced power electronics and control that DC motors are left behind in the competition.

Despite this, DC motor drives can still be found in modern EVs such as Danavolt of Peugeot Citroen [17-18].

Induction Motors: IMs are characterized with three-phase AC (Alternating Current) windings arranged on the stator and short-circuited copper windings (or cast aluminum bars) on the rotor, as presented in Fig. 3(b). In general, any electrical machines with brushes or commutators are not preferred because of their high maintenance requirements. Therefore, squirrel-cage IMs are chosen for consideration in the following texts.

It is commonly accepted that squirrel-cage IMs are renowned for their simplicity, ruggedness, cheapness and reliability so that they are used extensively in industrial drives. Their excellent field-weakening performance and low manufacturing costs make them a competitive candidate for EV motor drives. Nowadays, IMs can achieve similar torque speed control as the DC motor drives. For example, the speed range can be extended beyond the base speed using field weakening as the field vector can be decoupled from torque vector by vector control. Regarding the efficiency, it can be high at the high speed and low torque range (due to reduced copper and core losses) while, at the low speed high torque range, the efficiency reduces due to increased rotor losses [19].

An exhaustive review of EV motor drives [16] and a survey of experts' opinions [1] all concluded that induction motor drives are favored in EV propulsion applications because of their low cost, high reliability, mature manufacturing and power converter technologies. However, their disadvantages are low efficiency, low power factor, and low inverter usage [16,20-21], limiting their use in large motor drives and high-speed operations of EVs.

Examples of IM driven EVs are Silverado of Chevrolet, Durango of Daimler Chrysler, X5 of BMW, and Kangoo of Renault [16].

Permanent Magnet Motors: PM synchronous motors install PMs on the rotor and three-phase AC windings on the stator, as shown in Fig. 3(c). Rare-earth neodymium magnet (NdFeB) is commonly used in high-performance PM motors. If the AC currents feeding into the PM machine terminals are of sinusoidal shape, the motors are called the BLAC (Brushless AC) motors. If the AC currents are of rectangular or trapezoidal shape, the motors are called the BL DC motors. Both motors can be identical in hardware configuration and different current waveforms of supply can be achieved by modifying control strategy in software. More details of different PM motor design features are given in [22].

PMs can be utilized either on the surface of the rotor or in the rotor. SPM (Surface-Mounted) designs have the magnet within the main flux path and consequently the magnetic circuit reluctance is high. In highly cooled machines the available armature to MMF (Magnetomotive Force) is high, offsetting the reluctance. 1.0 per unit armature inductance is easily possible in a water jacket cooled surface magnet design. Consequently, flux weakening is not a problem. SPM motors would yield a small rotor diameter with low inertia (thus good dynamic

performance). Using IPM (Interior Permanent Magnet) in flux concentrating mode creates a high magnetic loading and reactance. The increased reaction flux unfortunately leads to the early onset of saturation once armature current is applied, offsetting much of their advantage. These motors can provide higher per unit inductances and thus field weakening capability [23].

In essence, it is beneficial to match the waveforms of supply and back EMF. In the vector control for field-weakening operation, d-q coordinate transformation is needed so that a sinusoidal current waveform is particularly favored in real-time implementation. In this regard, BLAC motors are superior to BLDC motors in EV propulsion drives [22]. If the necessity for d-q coordinate transformation is removed [24], BLDCs are preferred since they can produce a higher torque than BLACs [24-25].

Overall, PM motors are suited for EV propulsion owing to their high torque and power density, high controllability, high torque/inertia and torque/volume ratios, low weight and size. They are particularly suited for in-wheel direct drive applications [26-30]. However, the main magnetic field in PM motors is fixed (due to PMs) so that their high speed range for constant power operation is rather limited. With field weakening, it is possible to extend speed range to 3-4 times the base speed [16,30-38]. When a vector control scheme is used for field weakening operation, a high d-axis demagnetizing current is applied. This would increase not only the conductor power loss but also the risk of demagnetizing the PMs. Fundamentally, limited reserve of rare earth materials and high costs of rare-earth PMs limit the widespread of PM motors for mass-production cost-sensitive markets such as EVs.

PM BL motor drives are widely found in Japanese EVs such as Tino of Nissan, Insight of Honda and Prius of Toyota [16].

Reluctance Motors: RMs have a distinctive rotor structure which is stacked from laminated silicon steel. The rotor is salient and operates on the basis of reluctance torque. If the stator is of round structure and is fed with a multi-phase AC supply, they are called synchronous reluctance machines. If the stator also has salient poles, the machine is called SR (Switched Reluctance) machines, as shown in Fig. 3(d). Synchronous RMs utilize sinusoidally distributed windings as in induction or synchronous machines while SR motors use concentrated windings wound around the stator poles.

For synchronous RMs, the rotor always operates at synchronous speed and thus no EMF is induced in the rotor (thus no joule loss). But these motors have limited saliency ratio and low power factor [39]. The SR motor has been a subject of extensive research [40-50] in various drive applications and is now gradually penetrating into the EVe market.

The fact that reluctance machines use neither windings nor permanent magnets on the rotor enables them to withstand large thermal or mechanical stresses, or high temperatures. The SR motor has salient poles on both the stator and rotor, and inherently independent phase windings. When utilizing unipolar excitation currents, a simple converter topology with two switches/phase can be adopted, giving further independence between phases and fault tolerance. If a short circuit occurs on one phase, the motor can still function with a reduced torque capability. An added benefit is the elimination of shoot-through faults since the converter phase-leg switches is connected in series with the motor phase winding. Reluctance motors can offer high reliability, simplicity and high speed potential [1]. Their high speed range can be extended to up to seven times the base speed [52], which is particularly useful for transportation vehicles.

Compared to PM motors, an equivalent SR motors are approximately 50% larger than PM motor [41] because both magnetizing current and torque-producing current must be supplied by the stator windings. A quantitative performance comparison is shown in Fig. 4. Compared to IMs, SR motors have much smaller end-windings, less coupling between phases, and lower rotor loss, higher torque density and efficiency, making them attractive for EV applications. Nonetheless, inexpensive SR machines are offset by their costly power converters and controllers owing to the need for relatively complex supply waveform and accurate rotor position. Furthermore, they also produce high torque ripples, acoustic noise [52], and high EMI (Electromagnetic Interference).

An example of using the SR motor drive in EVs is ECO mmodore of Holden [16].

4. MOTOR DRIVE CONSIDERATIONS

A commercial successful EVE must have an electrical motor drive coordinated with power train, battery and power electronics in an appropriate system configuration [53].

Choice of the Powertrain: Typically, an electric power train comprises a geared drive motor, a power converter, and a battery for EVs. For HEVs, they also have an ICU, an energy storage for HEVs, as shown in Fig. 5.

EMs can be designed to operate at high speed. This can significantly reduce the mass and volume of the geared motor drive at the expense of increased mechanical power losses associated with the clutch, reduction and differential gears. For example, a HEV using a two-stage planetary gear and differentials is favored in [54]. On the

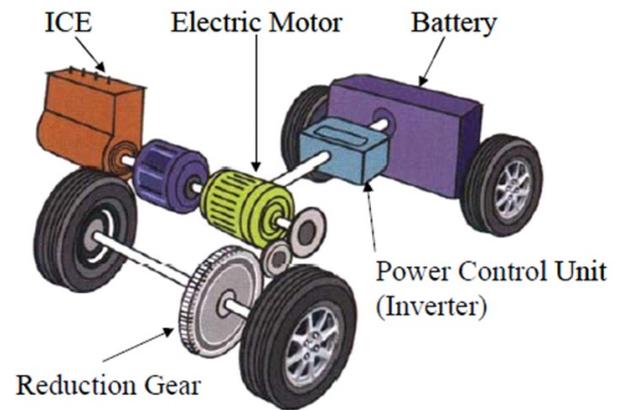


FIG. 5. ILLUSTRATION OF A HEV STRUCTURE [16]

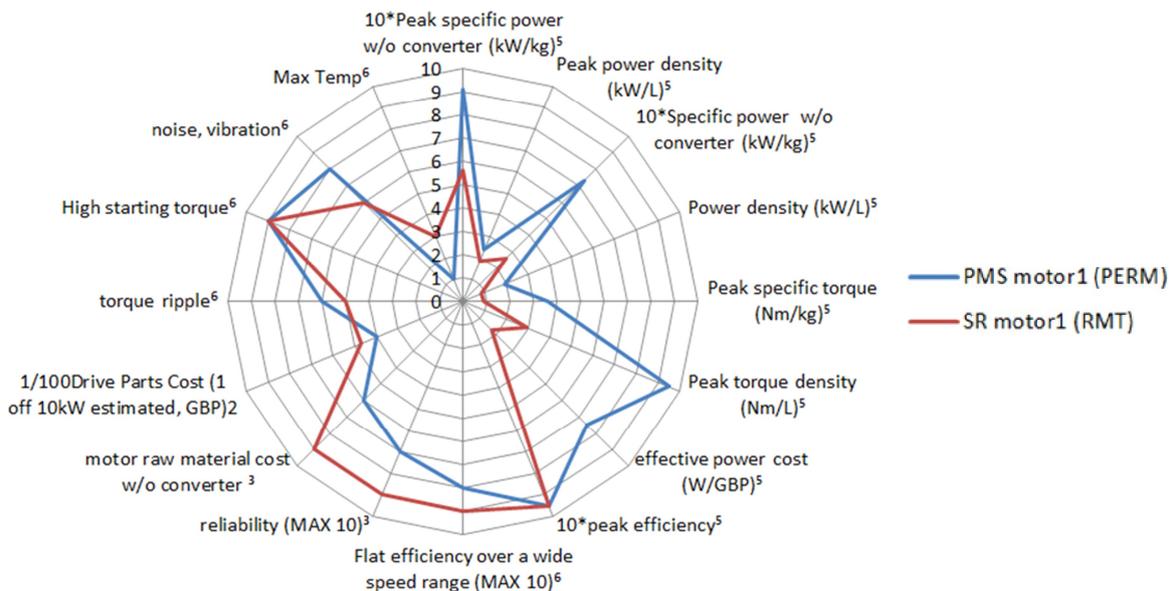


FIG. 4. PERFORMANCE COMPARISON BETWEEN PM AND SR MOTORS [51,61,65]

other hand, the direct drive configuration would eliminate the gears and power transmission system but the EM can be very large and heavy, calling for motor drives with a very high power density. This needs almost exclusively a high-performance PM motor. Arguably, a one-stage geared motor drive (without differentials) may be a very good compromise in this regards.

Choice of the Battery System: The performance of a battery system has always been a major limiting factor in any EVs. The choice of the power supply is dictated by the battery used. Currently, a lithium-ion (Li-ion) battery is capable of providing a voltage output of 3-4V, a maximum power of 1.5 kW, and an energy density of 100-120 Wh/kg. Its voltage level is nearly three times more than a nickel-cadmium battery [55-56] and its maximum energy storage is three times more than a copper-acid battery. A detailed comparison of the three major EV batteries is tabulated in Table 2.

With battery power, the usable charge voltage ranges from 25-40%. A PWM controller is used to convert this level of voltage into the supply voltage for the motor drive where typical electric cars use 400-800 A controllers with a voltage from 120-300V.

Power Electronics: EMs cannot properly function without fast and precise power electronic converters and controllers. As an enable technology, power electronics plays a key role in converting power from electrical to mechanical in an efficient manner. There are two drive forces behind this. First, there is an ongoing trend to replace traditional mechanical and hydrologic drives with electrical drives moving towards more EVs. The other is ever increasing demand for functions, comfort and commodity levels for passenger vehicles [57-59].

In general, an IGBTs (Insulated Gate Bipolar Transistors)-based VSC (Voltage Source Converter) is commonly used for electrical propulsion applications. Typical specifications of such a voltage source inverter for AC drives are listed in Table 3.

As the cost of power electronics continues to reduce, the full utilization of these devices are no longer an obstacle. There is an ongoing trend to integrate electrical motors with power electronic controller, named the “integrated motor drive”. However, reliability of these key components is critical to the drive system’s healthy operation. The integrated in-service condition monitoring and fault prognostic detection for electrical machines and power electronics are becoming increasingly important.

TABLE 2. COMPARISON OF MAJOR EV BATTERIES

Type of Battery		Energy Storage (Wh/kg)	Power Density (W/kg)	Price (\$/kWh)
Lithium-Ion	Saft	77	1550	2000
	Saft Shin-Kobe	140 3920	56 2000	476 2000
	Shin-Kobe	105	1344	2000
Nickel-Metal	Panasonic	46	1093	1500
	Panasonic Ovonic	68 1000	45 1500	240 1500
	Ovonic	68	200	1500
Lead-Acid	Panasonic	26.3	389	150
	Panasonic	34.2	250	150

5. TRENDS OF ELECTRIC MOTORS FOR ELECTRIC VEHICLES

In spite of significant R&D effort in developing EVs, it will be a long way to achieve all EVs. As the core element in electrical drives, EMs have been improved in many different ways. One attempt is to re-arrange the magnetic flux configuration and the other is to integrate different machine features. These will continue to be developed for many years to come.

Flux Configuration: Conventionally, EMs use a radial-flux configuration and their rotor is placed inside their stator, as is presented in Fig. 3. However, EV applications offer a unique opportunity for the machine designer to devise novel machine topologies. Axial-flux [60-63] and transverse-flux [26,64-65] motors are two examples of such attempts.

In an axial flux machine, magnetic flux flows axial to the direction of rotation of the rotor. For instance, AFPM (Axial Flux Permanent Magnet) motors are characterized with large diameter and high pole numbers. The stator and rotor disks are generally arranged in a sandwich structure. In the literature, the machine geometry with a stator sandwiched between two rotors is termed the Torus geometry while the geometry with a rotor sandwiched between two stators is termed the Kaman geometry [66].

In principle, the Torus geometry can use both disk surfaces of the stator and thus provide more torque and better system efficiency than a Kaman geometry.

As discussed previously, PM motors are well suited for direct drive in-wheel PM motors. The transverse flux machines offer the prospect of very high specific loadings (25Nm/kg has been measured on prototypes). They derive much of their benefit from high pole number but this limits maximum speed. As direct drives their promise is clear, but more development is necessary before they can compete with higher speed conventional machines. Transverse flux motors have high torque density and favorable characteristics in terms of maximum torque and efficiency.

An example of transverse flux PM machine is shown in Fig. 6(a-b). The transverse flux motor is compact and of low cost. Compared to PM motors, they use much less magnets for the same output torque. However, high temperature magnets would need to be used to allow operation of the same coolant circuit as the ICE. It would be beneficial to develop ferrite-based transverse flux motors to lower the cost. In general, transverse flux motors have a good geometry for in-wheel mounting for direct drive. But they suffer from low inductance, poor power factor which increases the power rating of the associated power converter [67].

TABLE 3. SPECIFICATIONS OF IGBT INVERTERS [62]

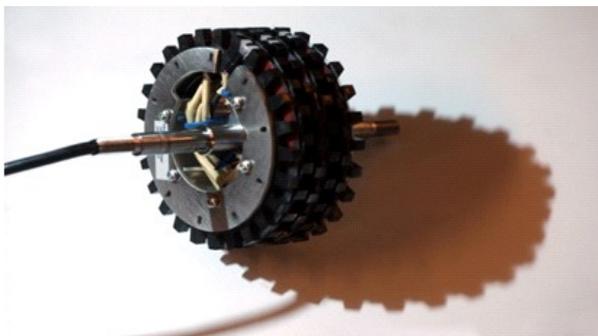
Parameter	Value
Blocking voltage	1200V
DC link voltage	170-320V
On-state current	Up to 425A
Switching frequency	8000Hz
Cooling system	Liquid cooling (50% glycol, 50% water)
Inlet temperature of the coolant	85°C
Volumetric flow rate	8L/min
Mass (including controllers)	11kg

Hybridization of Different Machine Features: It is well understood that four types of machines all have their merits and drawbacks. For example, DC series motors have good torque-speed characteristics and separate torque and field control; squirrel-cage IMs have robust and BL rotor structure and are cheap for mass production; PM motors are compact and powerful; and SR motors have simple and fault tolerant rotor structure as well as excellent constant-power operation. It would be ideal to integrate some appealing features of these into one machine.

A hybrid of PM motor with a series DC motor is given in [68] which adds an electric excitation field from the stator to superimpose on the PM excitation field. By doing so, field-weakening control for PM motors is achieved and the high speed range is extended despite the risk of



(a) CONSTRUCTION



(b) PRODUCTION STATOR

FIG. 6 TRANSVERSE FLUX PM MOTOR FOR ELECTRIC BICYCLES [67]

demagnetization of PMs. The integration of PM and IM motors are described in [39] to take advantage of IMs' self-starting feature in PM motors. A hybrid of synchronous reluctance motor with PM features is given in [69] and its topology is shown in Fig. 7. A hybrid of SR motor with PM features is given in [70-71] and its topology is shown in Fig. 8.

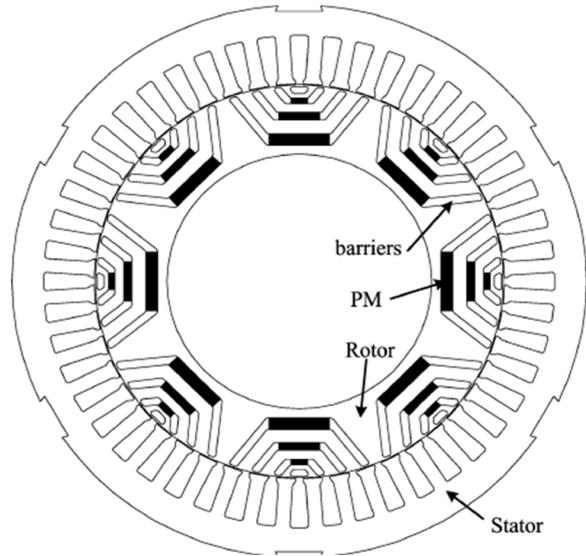


FIG. 7. CROSS SECTION OF PM-ASSISTED SYNCHRONOUS RELUCTANCE MACHINE

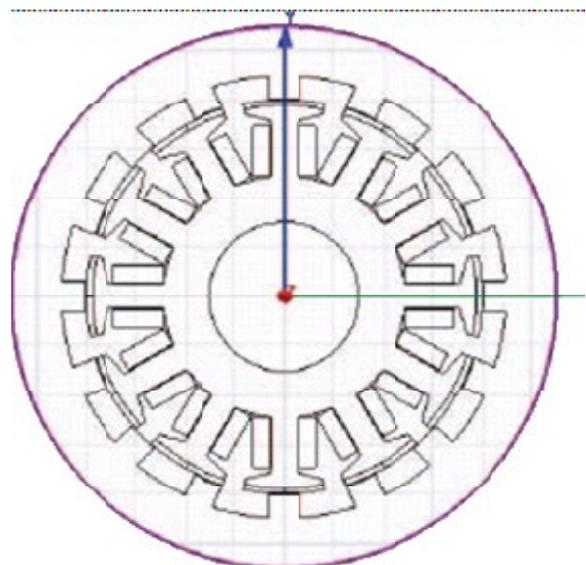


FIG. 8. CROSS SECTION OF PM-SR MACHINE

A performance comparison of the four electrical motor drive technologies for EV applications is summarized in Table 4.

Latest Research: The slogan of decarbonization and to electrify the whole thing has come to be a common practice with cleaner and most effective and efficient energy system there is an emerging concept which is being developed in a dramatic enhancement in transportation, buildings and industrial sector [72]. Various machine design, batteries and energy management methodologies have been proposed to address the design challenges of driving range and battery lifetime in EVs. Two complementary battery packs with different chemistries and the necessary electronic control based on lithium-ion and Zinc air battery have been considered in [73] as a limited cycle range. Additionally, the driving behaviors which is the major factor in terms of future vehicle speed has been proposed in [74]. As the EM is the chief part in the EVs which actually consumes high energy during motoring mode and generates power for the duration of regenerative mode and braking. The tesla dual-motor drive system has actually developed a milestone for pure EVs such as all-wheel drive P100D Model-S employs two IMs with specifically diverse

features of torque-speed and efficiency map to significantly boost the acceleration and dispense existing electric power to maximize torque in relation to the road grip conditions and weight transfer in the car [75]. An effective method to improve the extended driving range and energy efficiency is of great importance an IM has been proposed based on power loss characteristics in [76]. Furthermore, with regard to motor control various control schemes have been developed which improves the efficiency [77].

Future Direction: The results presented at this time reflects an effort to explore the potential implication of the EVs. The EV do not burn fossil fuels and they are very clean at local level, so as per EEP (European Environmental Agency) which has predicted that EV possibly will assume 4-5% of the total electricity consumption up to 2030 [78]. Therefore, saving in conveyance charges will value in a long-lasting boost in annual disposable revenue [79]. In future, together with electric cars, autonomous vehicles and self-driving cars will have their appearance by 2050 [80]. Although, both the expertise are not collectively reliant, but the electric cars are much candidates to be the self-driving cars. Whereas as autonomous vehicles require charging

TABLE 4. PERFORMANCE COMPARISON OF MOTOR DRIVE TECHNOLOGIES

Performance	DC	PM	IM	SR
Power Density	Low	High	Low	Medium
Torque Ripple	Low	Medium	Low	High
Acoustic Noise	Medium	Low	Low	High
Overload Capacity	High	Medium	High	Low
Controllability	High	Medium	High	Low
Max Speed	Medium	Low	High	Very High
Speed Range	Medium	Low	Medium	High
Size	Medium	Small	Medium	Large
Reliability	Low	Medium	High	High
Efficiency	Low	High	Medium	Medium
Cost	Medium	High	Low	Medium

infrastructure then the EV which are already available in the market. The self-driving cars will require its separate charging point and therefore, charging point will need to be properly structured at different locations. There will not be crucial to buy personal or private car in future. Everybody will be able to use the smartphones to get a car for any of the mobility needs. However, the complete electrification of transportation would require enormous modifications power generation to grid design and operation [72]. As the future scenarios can only be considered in terms of probabilities so the disruption might happen in lithium-ion batteries because of step changes in these technologies (as happening in solid-state batteries and artificial-intelligence processing units) [79]. The new design strategy and multidisciplinary optimization electromechanical energy conversion system which can be best fitted for the EV traction technologies. Additionally, multiphysics analysis of multiport electrical machines and system with emphasis on thermal design and electromagnetic compatibilities with structural reliabilities need to be carried out which would be very beneficial for the performance of EVs.

6. CONCLUSIONS

This paper has presented a performance comparison of motor drive technologies including DC series motors, caged IMs, PM and SR motor drives used for EVs, with a particular focus on the choices of candidate machines and their drive topologies for passenger cars.

EV applications demand high power density, high efficiency and high reliability while aiming to reduce overall costs and environmental impacts. From the analysis and comparison, four major types of electric drive systems can meet these stringent requirements and also provide significant technical and economic improvements over conventional ICEs. Historically, DC, IM and PM drives

have been used for electrified transportation at different stages. At the stage, DC motors are hardly found in the automotive market while both induction motor drives and BL PM drives are widely adopted. SR motor drives are a relatively new topology and have shown their superiority in EV applications. Nowadays SR motors are making inroads into EVs but still need time to improve their performance and to gain in-service experience. Overall, IM drives are especially favored by the industry and EV experts for general-purpose EVs. For in-wheel direct drives, PM motors may be the best solution striking a balance between compactness and total capital cost. The R&D effort is needed to focus on reducing manufacture costs and minimizing the use of rare-earth PMs. Ultimately, EVs are a cost-sensitive market, initial and operational costs are the key limiting factors. In the long run, the development of all EVs requires a multi-disciplinary approach which involves socio-economic analysis, human behaviors and HMI.

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