A SURVEY ON COMPARISON OF ELECTRIC MOTOR TYPES AND DRIVES USED FOR ELECTRIC VEHICLES

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***Abstract*--In this study, Switched Reluctance Motor (SRM), Induction Motor (IM), Brushless DC Motor, and Permanent Magnet Motor (PM), and their drives have been compared with the efficiency, cost, weight, cooling, maximum speed, reliability, fault tolerance, power ratings, and vehicle acceleration time. Hence, a comprehensive literature research on motor types and their drives used in EV has been made. According to these researches, some conclusions have been obtained. It has been seen that PM BLDC motors and their drives are the most efficient and have high power density, brushless DC motors and their drives have low cost, IM is appropriate for controllability and cost, the weight of SRM is low, its reliability is high, it operates fault-tolerance and according to the acceleration time, its performance is better than IM and BLDC. Hence, SRM is the most appropriate motor for EV.**

***Keywords*- Electrical vehicle motors and their drives, comparison**.

I. Introduction

According to the shape of driving of the vehicles, engines are divided into three groups called internal combustion engine vehicles (ICEV), electric vehicles (EV) and hybrid electric vehicles (HEV). While conventional vehicles are driven by internal combustion engines (ICE), EV are driven by an electric motor or a few electric motors. HEV are driven by both an electric motor and an internal combustion engine [1]. Land vehicles need constant power with regard to acceleration and gradability. Therefore, ICEVs are not convenient for producing this torque and speed. If some motors are designed appropriately, an extended constant range can be obtained.

Desired features of motor drives used for EV are a high power density, a fast torque response, a high instant power, including constant-torque and constant-power regions, low cost, robustness, high efficiency over the wide speed, a high torque at low speeds for initial acceleration and gradeability and reliability [3]. If compared with DC motor drives, AC motor drives have some advantages such as higher efficiency, less maintenance need, robustness, reliability, higher power density, effective regenerative braking [2]. In this paper, a survey on selection of motors and drives in EV has been implemented. AC, DC motors and their drives have been compared.

II. Motor Types Used in EV

A. DC Motor

DC motors are one of the motor types used for EV applications. Before advances in power electronics, they were commonly used in variable speed applications [4]. They are preffered in EV due to simple control and robustness. DC motors are divided into two types called brushed and brushless DC motors. The brushed DC motors provide high torque at low speed and have an appropriate torque-speed characteristic. On the other hand, they have some drawbacks such as large structure, low efficiency, low reliability, costly maintenance requirement due to the brush and collector structure. Furthermore, friction between brush and collector limits the maximum motor speed [2]. The torque-speed characteristic of the brushless DC motor is shown in Fig. 1.

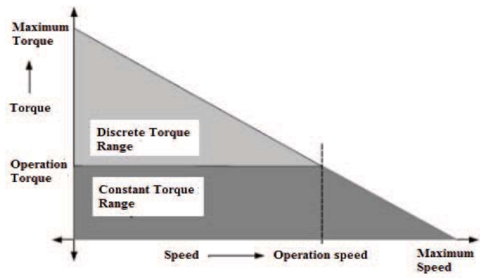

Figure 1. Torque-speed characteristic of brushless DC motor

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B. Induction Motor (IM)

Induction motors are commonly used in EV applications because of simple structure, reliability, robustness, less maintenance requirement, low cost and operation at poor environmental conditions. The torque-speed characteristic has been shown in Fig. 2. The torque and field control can be divided by vector control methods. Speed range may be extended by flux weakening in the constant power region. IM has negative features such as low efficiency compared with PM, high loss and low power factor. To overcome these problems, dual inverters are used for the purpose of extending constant power, and rotor losses are reduced in design stage [2].

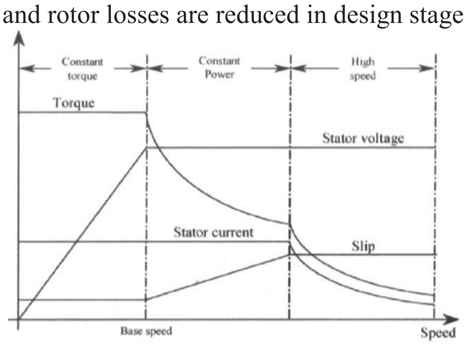

Figure 2. Different characteristics of induction motors.

C. PM Brushless DC Motor (PM BLDC)

Power density and efficiency of PM BLDC motors are high. Their efficiency is higher than IM due to not having rotor winding and rotor copper losses. These motors have a short constant power range because of limited field weakening capability resulting from the presence of the PM field which can be weakened by a stator field. Thus, as shown in Fig. 3, the constant power region is short. The operation region at constant power can be extended by a conduction-angle control three to four times in Fig. 4 [1].

Magnets of PM BLDC motors obstruct to obtain a high torque from the motor. Moreover, there are some disadvantages such as the mechanical forces and cost of magnets. Because of the breaking possibility of magnets, the rise of centrifugal forces at higher speed has a risk in terms of driving safety. In addition, magnets are prone to high temperature. Due to the high operating temperature, remnant flux density reduces; therefore, the torque capacity of the machine also reduces [13].

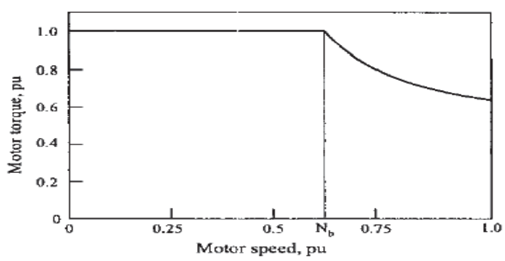

Figure 3. Typical characteristics of PM BLDC motor [5].

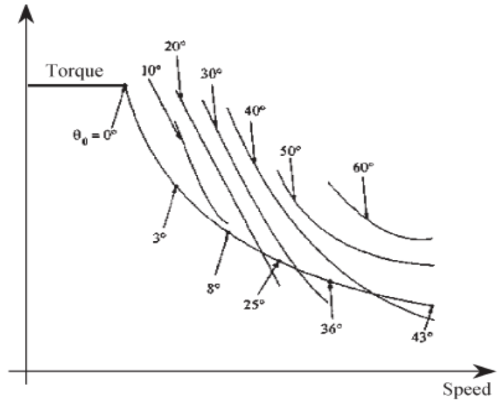

Figure 4. Torque-speed characteristic of a PM BLDC motor drive with conduction angle-control [3].

D. Switched Reluctance Motor (SRM)

SRMs have main advantages for EV such as simple control, a wide constant power region at high speed, fault tolerance, effective torque-speed characteristic, and robust construction.

Owing to its higher torque component, SRM has gained much prominence. Hence, it is used for a lot of applications such as wind energy, starter/generator systems in gas turbin engines, high performance aerospace applications [14].

SRM's efficiency is over 95% and it is equivalent to the IM [4]. For these features, SRM is an appropriate motor type for EV applications. Due to not having brush, collector and magnets, there is no maintenance requirement. Hence, the production cost is low.

Not having magnet provides that motor can be operate at high speed. The high rotor inductance ratio allows sensorless control to perform. There aren't rotor copper losses due to the conductor in rotor winding; therefore, the rotor temperature is lower than the other motor types. Low inertia is significant in variable reference speed applications to capture reference speed. The rotor of SRM has also lower inertia than the other motors. There isn't a connection between the phases; therefore, once one of the phases fails, the motor continues to operate [7]. On the other hand, acoustic noise, vibrations and high torque ripple due to the salient-pole rotor and stator occur, but these are not crucial problems for EV. Besides, a drive is required at initial acceleration and gradeability to implement at constant power. The constant power region can be extended by proper motor design [6]. The torque-speed characteristic of SRM is shown in Fig. 5 [3]. This characteristic is so convenient for EV applications. Wide constant power region allows to operate at high speeds [1].

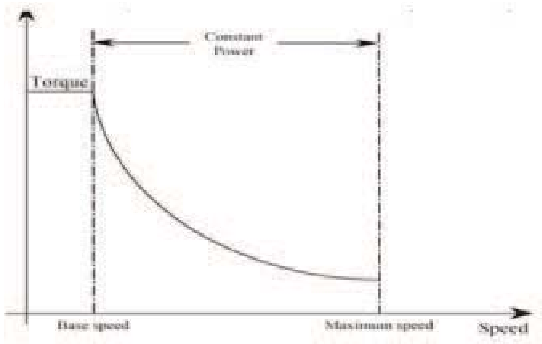

Figure 5. Typical torque-speed characteristic of an SRM

III. Desired Characteristics and Output Characteristics of Motor Drives Used in EV

Vehicle performance in EV is examined by torque-speed or power-speed characteristic. Maximum grade and maximum speed are two important design factors for defining the torque-speed curve [11].

The vehicles must operate in constant power for initial acceleration and proper gradeability. Desired output characteristic of motor drives used in EV is shown in Fig. 6. The motor drive is desired to have high torque at low speed for gradeability and acceleration and high power at high speed for cruising and wide speed range under constant power. The output characteristic of EV drives used in industrial applications is also illustrated in Fig. 7.

The motor is operated in constant power region beyond base speed up to maximum speed. The constant power operation varies with motor type. Some motor drives remove from constant power and entire the natural operation before reaching maximum speed. In the natural operation, the maximum torque decreases proportional to the square of speed. This may also cause reduction of total power requirement [1].

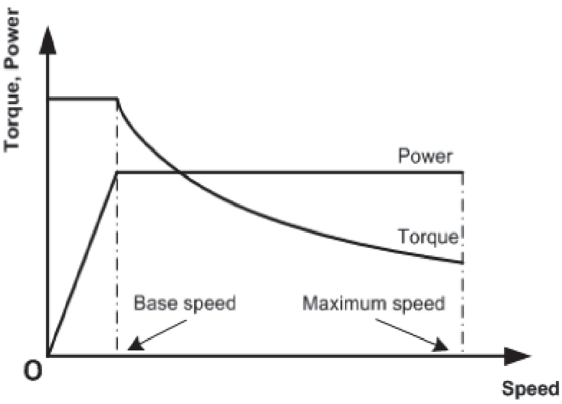

Figure 6. Desired output characteristics of electric motor drives in EVs [1].

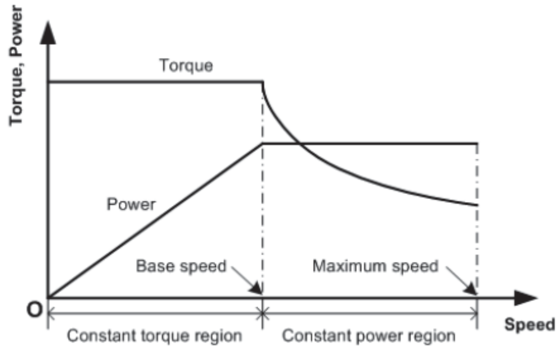

Figure 7. Typical performances of electric motor drives in industrial applications [1].

According to the output characteristic of EVs, if the constant power region ratio increases, power requirement for acceleration performance decreases. Hence, the torque requirement, converter cost, motor size, and volume increase.

IV. Comparison of Motor Types Used in EV

Motor types are used for various applications such as wind turbine, aerospace, robotics, tool-domestic. In a study in 2013, the motor types used in these different applications have been examined in TABLE I. It is seen that the most proper motor type for EV is SRM [15].

TABLE I. Comparison of EM used in different applications [15].

	IM	PMSM	SRM
EV	2	1	5
Wind turbine	5	4	3
Aerospace	2	4	3
Robotics	1	5	2
Tool-domestic	1	4	2
Others	3	4	3
TOTAL	**14**	**22**	**18**

According to a study on the motor types used for EV in 2010, comparison of IPM, IM and SRM has been made in taken motor sizes, 1500 rpm and 6000 rpm speed and maximum power. The comparison of torque, iron loss, copper loss, efficiency and current density has been illustrated at TABLE II. As seen in TABLE II, the torques of IPM and IM are higher than SRM at 1500 rpm. IM has higher copper losses. Once we look at the efficiency, the most efficient motor is IPM. The overall motor and electronics efficiency influences the battery weight. Every 1% lower efficiency requires 1% more battery [16]. At 6000 rpm, it is seen that SRM provides the best torque value. The efficiency of IPM is the highest at high speed [10].

TABLE II. Comparison of performances at 1500 and 6000 rpm at maximum power [10].

Speed=1500 rpm						
Variable	Torque (Nm)	Current (Arms or Apk-SRM)	Iron Loss (W)	Copper Loss (W)	Eff. (%)	RMS current density (A/mm^2)
IPM	303	141.1	198	4328	91.3	15.7
IM	297	164.8	148	8591	83.1	15.8/12.1
SRM	294	300	404	7653	85.2	20.1
Speed=6000 rpm						
Variable	Torque (Nm)	Current (Arms or Apk-SRM)	Iron Loss (W)	Copper Loss (W)	Eff. (%)	RMS current density (A/mm^2)
IPM	45.6	31.8	953	219	96.1	3.75
IM	50.8	47.1	439	730	95.2	4.51/3.72
SRM	52.1	60	4074	306	88.2	4.02

In a study, 0-60 mph acceleration time, power and input KVA ratings of SRM, IM, BLDC motors have been examined in TABLE III. While Design 1 which has the narrowest rotor poles requires least amount of time for the acceleration, Design 6 which has the longest constant power range requires longer time for the initial acceleration due to its lower power rating. These are among the 6-4 designs. The 8-6 designs have much higher power rating than the 6-4 designs. Therefore, the acceleration time is much lower inspite of lower constant power range. SRMs indicate equal or better performances than IM and BLDC motors [17].

TABLE III. Motor power ratings and vehicle acceleration time [17].

SRM Design	Accl. Time (s)	SRM Power (kW)	SRM (kVA)	IM Power (kW)	IM (kVA)	BLDC Power (kW)	BLDC (kVA)
1	13	42.1	69.8	57.88	72.35	75.5	83.9
2	13.25	42.56	69.86	56.9	71.13	74.43	82.7
3	13.48	42.61	69.9	56	70	73.27	81.41
4	13.58	45.88	69.85	55.68	69.6	72.78	80.86
5	13.85	39.1	64.76	54.7	68.38	71.46	79.4
6	14.78	34.6	59.35	51.68	64.6	67.39	74.88
7	14.1	38.98	64.68	53.85	67.3	70.34	78.15
8	15.01	35.38	59.32	50.1	62.6	66.4	73.77
9	10.1	68.12	101.4	72.7	90.88	95.67	106.3
10	8.74	69.95	109.3	83.04	103.8	109.6	121.8

As seen from TABLE IV, according to another study on power density, efficiency, controllability, reliability, cost, DC, IM, PM and SRM have been compared in 2006. As we examine TABLE IV, IM comes first in terms of all characteristics in EV applications, but one of the most important subjects is driving safety in EV. Hence, if we look at the reliability of the motors, SRM like IM takes first place and provides driving safety [3].

TABLE IV. Electric-propulsion systems evaluation [3].

Propulsion Systems	DC	IM	PM	SRM
Characteristics				
Power Density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	5	3.5
Controllability	5	5	4	3
Reliability	3	5	4	5
Technological maturity	5	5	4	4
Cost	4	5	3	4
Total	**22**	**27**	**25**	**23**

Besides these properties, the maintenance need of SRM is less due to not having brush collector and magnet. As it is known that torque generation is implemented by coils which is parallel to the rotor. Furthermore, coil ends and the connection between coils have a minor effect on the torque. Losses increase because of rising conductor length and the efficiency of motor reduces. SRM has short coil ends compared with other motors. The losses of coil ends are low because of cross-link and short total winding length. There isn't conductor in the rotor. Therefore, the rotor temperature is low and rotor can be easily cooled [7]. This is a crucial problem for the other motors.

SRM can be operated at high speeds in wide constant power region. The speed of IM is generally low. Features of SRM such as the fault-tolerance operation and reliability are very important for EV. For phase windings of SRM are independent of each other, failure on one of the phases doesn't affect motor operation. The motor continues to operate until maintenance is done. Motor cost is cheap, stability, and SRM operates in every environmental condition.

IM is commonly used in the industry due to its simple construction and less cost. Nevertheless, these are not very important technical priorities than the other motors [8].

V. Comparison of Motor Drive Systems Used in EV

In terms of efficiency, weight, and cost, a comparison of the motor drives has been made in TABLE V. Characteristics of motor drives have been switched from 1 point to 5 point [1].

TABLE V. Comparisons between four types of electric motor drives [1].

Index	DC Motor Drives	IM Drives	PM BLDC Motor Drives	SRM Drives
Efficiency	2	4	5	4.5
Weight	2	4	4.5	5
Cost	5	4	3	4
Total	9	12	12.5	13.5

As seen from TABLE V, the efficiency of PM BLDC motor drive comes first. DC motor drive has the lowest cost. SRM is convenient for efficiency and cost, and its weight is less.

TABLE VI. Comparisons between three types of electric motor drives [9].

	Rated speed (rpm)	**Maximum speed (rpm)**	**Constant power range**	**Power factor**
IM	1750	8750	1:5	0.82
BLDC	4000	9000	1:25	0.93
SRM	4000	20000	1:3 Rest in natural mode	0.6

In a second study, as seen in TABLE VI, while power factor for SRM is poor, maximum speed and rated speed are high in the constant power range. The extremely high speed operation and wide constant power range provide to cope with its low power factor operation.

Power factor of IM drives is good, but rated speed is low.

Although power density and efficiency of BLDC motor drives are high, it is not preferable for EV because of the limited constant power range [9].

In another study between interior permanent magnet synchronous machine (IPMSM) and IM, feutures given in TABLE VII show that IM has lower power factor and efficiency than IPMSM in low speed region. Current rating of inverter for IM should be higher than that of IPMSM in the same torque-speed range. However, it provides flexible flux control model [11].

TABLE VII. Comparison of IM and IPMSM based on a design data [11].

Speed=1500 rpm			
IPMSM	T_e=303Nm	I_{s_rms}=141.1A	η_{em}=91.3%
IM	T_e=297Nm	I_{s_rms}=164.8A	η_{em}=83.1%
Speed=6000 rpm			
IPMSM	T_e=45.6Nm	I_{s_rms}=31.8A	η_{em}=96.1%
IM	T_e=50.8Nm	I_{s_rms}=47.1A	η_{em}=95.2%

Features of IM and IPMSM have been compared in TABLE VIII. It is seen that IM provides efficiency optimization and control of regenerative braking by efficiency control. Having high efficiency of IPMSM at low speeds improves battery utilization and driving range. IPSM has better geometrical integration into engine cabinet and reduces total weight of vehicle.

Conversely, IPMSM has high cost due to magnets. Current rating is lower than IM.

TABLE VIII. Comparison of IM and IPMSM [11].

IM	**Advantages in EV**
For the magnetizing current is supplied by stator, IM has flexible efficiency control.	If state of charge is near maximum limit, efficiency of IM can be reduced by motor drive system in order to limit the return of regenerative energy. Efficiency optimization at light load conditions is possible by control of flux reference.
IM field weaking is controlled by reduction of magnetizing current.	Efficiency of IM is competitive against IPMSM at high speed region on torque-speed curve.
Cost competitive both in terms of material and production technology.	Economical Unlike IPMSM, material cost is independent of magnet price changes.
IPMSM	**Advantages in EV**
If IPMSM is compared to IM, it has high efficiency at low speeds.	Advantages for city cars where frequent start-stops occur at low speeds. This also improves battery utilization and driving range.
High torque/valume ratio, smaller sizes and lighter weight.	It has better geometrical integration into engine cabinet and reduces total weight of vehicle.
Current rating is lower than IM.	Lower current rating for inverter and improved battery utilization.

VI. Conclusions

In this study, electrical motor types and drives have been discussed and their features such as efficiency, cost, weight, operation and maintenance requirement, reliability, robutness, fault-tolerance, cooling, operation in wide constant power region, power ratings and vehicle acceleration time have been compared.

PM BLDC motor and their drives have the highest value in terms of the efficiency ,but being used by magnets causes additional cost and the maintenance requires.

Brushed DC motor also requires the maintenance due to brush and collectors. Hence, while their cost is high, brushless DC motors don't require the maintenance and their cost is low. DC motor drives also have the least cost.

The motors which have the least weight are SRMs. Furthermore, they have major qualities such as low cost, easily cooling, robustness, fault-toerance operation. One of the most important features for EV is reliability and SRM is one of the most reliable motors. Moreover, SRM drives are appropriate for cost and efficiency. A constant power range is more than four times the based speed which is demonstrated by the 8-6 experiment motor and according to the acceleration time, its performance is better than IM and BLDC [17].

To compare all of these features, the most widely used motor drives are IM and PM BLDC because the cost of

IM is less and PM BLDC motors, and their drives are efficient and have high power density. DC motor drives have one of the most mature technologies [12]. SRM is the most convenient motor for the weight, reliability, and fault-tolerance operation, and according to the acceleration time, its performance is better than IM and BLDC. These are more important features for EV. Therefore, SRM is the most appropriate motor for EV applications.

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