# Selection of Electric Motor Drives for Electric Vehicles

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***Abstract*-In this study, six kinds of the drivetrain systems of electric motor drives for EVs are discussed. Furthermore, the requirements of EVs on electric motor drives are presented. The comparative investigation on the efficiency, weight, cost, cooling, maximum speed, and fault-tolerance, safety, and reliability is carried out for switched reluctance motor, induction motor, permanent magnet blushless dc motor, and brushed dc motor drives, in order to find most appropriate electric motor drives for electric vehicle applications. The study shows that switched reluctance motor drives are the prior choice for electric vehicles.**

## I. INTRODUCTION

Conventional vehicles are driven by internal combustion engine (ICE) and thus they are also named internal combustion engine vehicles (ICEVs). The vehicle is named the electric vehicle (EV) if an electric motor or a few electric motors are used to drive wheels of a vehicle. In addition, the vehicle is named the hybrid electric vehicle (HEV) if both an electric motor and an ICE impel wheels of a vehicle. Electric vehicles are only discussed in this paper.

A system schematic of EVs is illustrated in Fig. 1 [1]. In EVs, the battery is the original energy source and provides electric power to electric motor drives and other equipments, such as lighting devices.

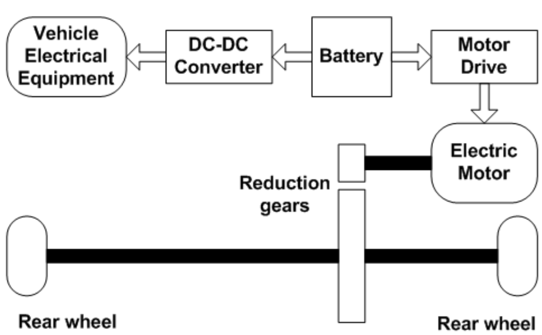


Fig. 1. Typical system schematic of EVs

The typical control schematic of EVs is depicted in Fig. 2. It can be observed that the typical control system of EVs includes five electric control units (ECUs), which are the Main ECU, Motor ECU, Battery ECU, Brake ECU, and Electric Equipment ECU. The main ECU controls the drive torque of EV by computing the motor torque based on information such as the accelerator opening and car speed command. The torque request value is sent to the motor ECU. In accordance with the drive output value requested by the main ECU, the motor ECU controls the motor drive to develop the desired torque. The motor drive can be used to achieve torque direct control (DTC). By coordinating the braking effort with the regenerative braking that is executed by the motor, the brake ECU controls such a manner that the entire brake torque produced by both the regenerative brake system and the conventional hydraulic brake system. The battery ECU monitors the charging and discharging state of the battery. Generally, the monitor of the battery includes the leak detection, the detection of abnormal voltage, the detection of the abnormal temperature, the detection of the abnormal current. The electric equipment ECU controls the DC-DC converter to generate a variety of DC voltage levels for lighting and other equipments.

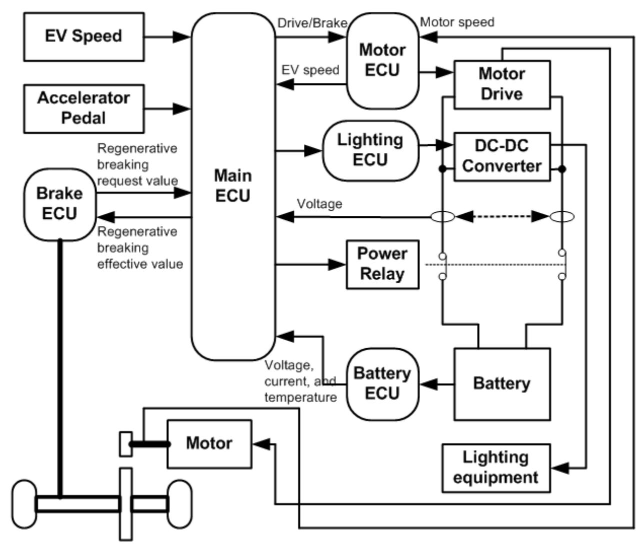


Fig. 2. Typical control schematic of EVs

As we know, there are various types of electric motors in industrial applications. They are used to drive all kinds of industrial devices. As for driving, all electric motors may be utilized to propel EVs. However, some performance indexes of EVs have to be taken into account when electric motors are

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applied to EVs, such as efficiency, weight, cost, dynamic characteristics of EVs. This study is focused on this issue.

The organization of this paper is written as follows. In the section II, the drivetrain systems of EVs will be described. After that, expected operating characteristics of electric motors for EVs will be given in the section III. The major request of EVs on electric motor drives will be proposed, too. Then, four types of electric motor drives for EVs are going to be discussed and evaluated to find the best electric motor drives for EVs in the section IV. Finally, the section V will summarize this paper.

## II. DRIVETRAIN SYSTEMS OF EVS

Internal combustion engine vehicles have the engine drivetrain configuration as shown in Fig. 3 [2].


Fig. 3. Typical drivetrain configuration of ICEVs

For EVs, output characteristics of electric motors differ from those of ICEs. Typically, the electric motor eliminates the necessity for a motor to be idle while at a stop, it is allowed to produce large torque at low speed, and it offers a wide range of speed variations. It may be possible to develop lighter, more compact, more efficient systems by taking advantages of the characteristics of electric motors. The choices of drivetrain systems in an EV include mainly: (a) propulsion mode, such as front-wheel drive, rear-wheel drive, or four-wheel drive; (b) number of electric motors in a vehicle; (c) drive approach, for instance, indirect or direct drive; and (d) number of transmission gear levels. Therefore, the possible drivetrain systems in EVs have the following six configurations.

### A. *Conventional Type*

For the conventional type of the drivetrain system in EVs, the conventional ICE is replaced by an electric motor, as shown in Fig. 4. This configuration does not change the typical structure of drivetrain system in ICEVs and hence is implemented easily.

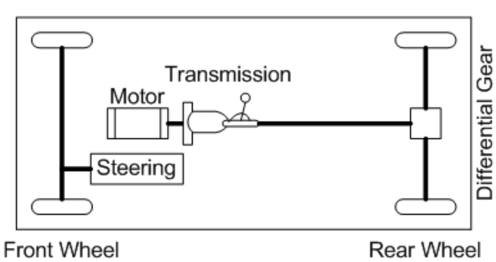


Fig. 4. Conventional type of drivetrain system in EVs

### B. *Transmission-less Type*

The transmission-less type of drivetrain system in EVs simplifies the conventional type, as the transmission is removed. Fig. 5 depicts the transmission-less type of drivetrain system.

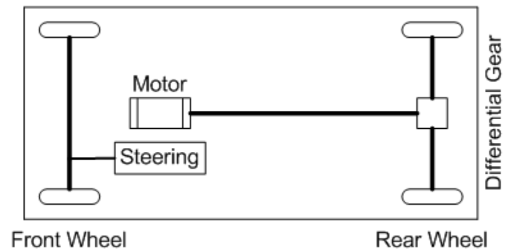


Fig. 5. Transmission-less drivetrain system

### C. *Cascade Type*

The transmission-less type can be simplified to the differential-less type if the differential gear is removed, as illustrated in Fig. 6. Two motors are in installed on body side and have joints provided to transmit power to the wheels to give a function equal to the differential. This type is also regarded as the direct drive type.

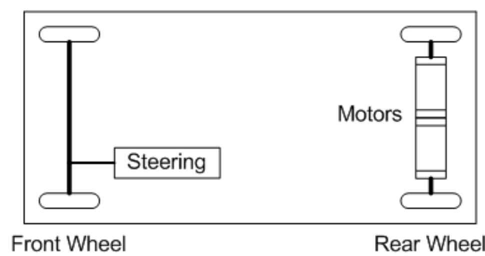


Fig. 6. Cascade-motors drivetrain system

### D. *In-wheel Type with Reduction Gears*

This type is obtained from the simplification of the transmission-less type. Two motors are fixed to the wheel side with reduction gears provided to drive the wheels, as shown in Fig. 7.

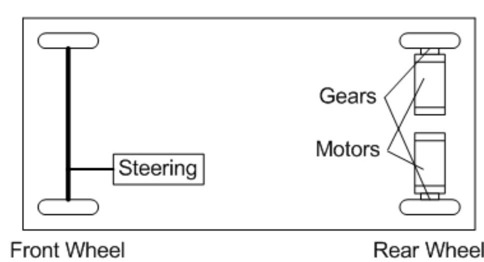


Fig. 7. In-wheel drivetrain system with reduction gears

*E. In-wheel Direct-drive Type*

In Fig. 8, rear wheels and motors are integrated so that rotations can be caused directly without resort to gear. This is the direct-drive type of in-wheel drivetrain system.

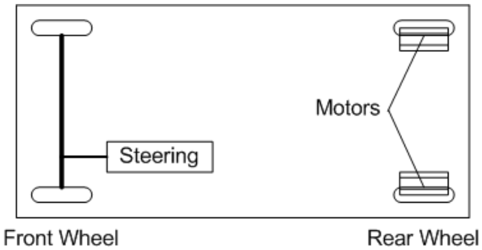


Fig. 8. In-wheel direct-drive drivetrain system

*F. Four- wheel Direct-drive Type*

Four in-wheel motors are used to directly drive four wheels, respectively, as shown in Fig. 9. It is possible that an electric steering is used to control the direction of the EV.

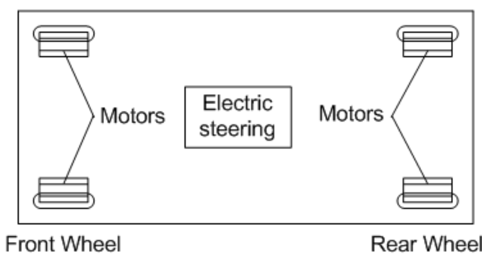


Fig. 9. Four-wheel drivetrain system

As development progress from Fig. 4 to Fig. 9, the drivetrain system takes up more compact dimensions and reduces power transmission losses. At the same time, the motor and the reduction gear must be reduced in size and weight. The direct-drive drivetrain system requires the motor which is light and develops a large torque. To fully take advantages of the wide range of output characteristics and small motor size arising from high maximum speed for electric motor drives, the drivetrain scheme with the single-level reduction gear is the good choice.

## III. EXPECTED CHARACTERISTICS OF MOTOR DRIVES FOR EVS

*A. Output Characteristics of Motor Drives in EVs*

Vehicle performance usually includes acceleration performance, evaluated by the time used to accelerate the vehicle from zero speed to a given speed (starting acceleration), or from a low speed to a given high speed (passing ability), gradeability, evaluated by the maximum road grade that the vehicle can overcome at a given speed, and the maximum speed that the vehicle can reach. In EVs, only traction motor delivers torque to the driven wheels. Thus the vehicle performance is completely determined by the torque-speed or power-speed characteristic of the traction motor. A vehicle, in order to meet its operational requirement, such as the initial acceleration and gradeability with minimum power mentioned above, operation entirely in constant power is needed [3]. Operation entirely in constant power is, however, not possible for any practical vehicle. For EVs, the desired output characteristics of electric motor drives are illustrated in Fig. 10. It can be observed that the EV motor drive is expected to be capable of offering a high torque at low speed for starting and acceleration, and a high power at high speed for cruising. At the same time, the speed range under constant power is desired as wide as possible. Ideally, eliminating the constant torque region would provide the minimum power rating of the motor, but this is not physically realizable.

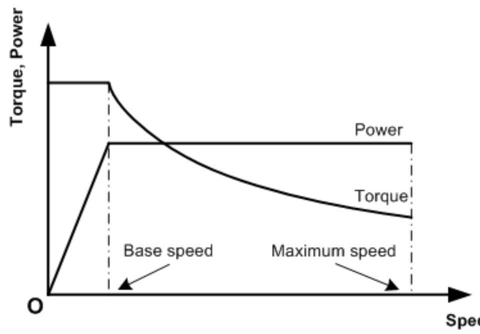


Fig. 10. Desired output characteristics of electric motor drives in EVs

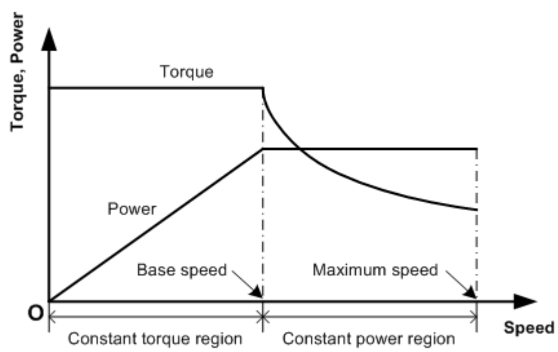


Fig. 11. Typical performances of electric motor drives in industrial application

For general electric motor drives in industrial applications, their output performances are shown in Fig. 11. Under the normal mode of operation, the electric motor drive can provide constant rated torque up to its base or rated speed. At this speed, the motor reaches its rated power limit. The operation beyond the base speed up to the maximum speed is limited to this constant power region. The range of the constant power operation depends primarily on the particular motor type and its control strategy. However, a few electric motor drives digress from the constant power operation, beyond certain speed, and enter the natural mode before reaching the maximum speed. The maximum available torque in the natural mode of operation decreases inversely with the square of the speed. Although the machine torque in the natural mode decreases inversely with the square of the speed, for some extremely high speed motors the natural mode of operation is an appreciable part of its total power-speed profile. Inclusion of this natural mode for such motor drives may result in a reduction of the total power requirement [4]. For indirect-drives, the requirement on the maximum motor speed depends on the maximum vehicle speed, the wheel radius, and the gear ratio. However, for direct-drives, the requirement on the maximum motor speed only depends on the former two parameters.

Thus, from the output characteristics of electric motor drives for EVs, the following valuable results can be concluded as follows [5]. a) The power requirement (rated power) for acceleration performance (acceleration time and acceleration distance) decreases as constant power region ratio increases. b) Conversely, the torque requirement (rated torque) for acceleration increases as constant power region ratio increases. This results in a larger motor size and volume. c) Passing performance (passing time and passing distance) suffers considerably as the constant power region ratio increases. d) A motor's maximum speed has a pronounced effect on the required torque of the motor. Low speed motors with the extended constant power speed range have a much higher rated shaft torque. Consequently, they need more iron and copper to support this higher flux and torque. e) As motor power decreases (due to extending the range of constant power operation), the required torque is increasing. Therefore, although the converter power requirement (hence the converter cost) will decrease when increasing the constant power range, the motor size, volume, and cost will increase. f) Increasing the maximum speed of the motor can reduce the motor size by allowing gearing to increase shaft torque. However, the motor maximum speed cannot be increased indefinitely without incurring more cost and transmission requirements. Thus, there is multitude of system level conflicts when extending the constant power range.

### B. *Requirements of EVs on Electric Motor Drives*

Selection of electric motor drives for EVs is a very important step that requires special attention. In fact, the automotive industry is still seeking for the most appropriate motor drive for EVs or HEVs. Previous literatures [2] [3] [6] discussed the major requirements of EVs on electric motor drives. Therefore, selecting the most appropriate motor drives for an EV is a challenging issue.

In this paper, the basic requests are summarized as follows: 1) a high instant power and a high power density; 2) a high torque at low speed for starting and climbing, as well as a high power at high speed for cruising; 3) a very wide speed range with constant-power region; 4) a fast torque response; 5) a high efficiency over the wide speed range with constant torque and constant power regions; 6) a high efficiency for regenerative braking; 7) downsizing, weight reduction, and lower moment of inertia; 8) a high reliability and robustness for various vehicle operating conditions; 9) a reasonable cost; 10) a fault tolerance; and 11) suppression of electromagnetic interface (EMI) of motor controllers.

## IV. Evaluation of Four Types of Motor Drives for EVs

As so far, four types of motor drives have been applied to EVs. They are brushed DC motor drives, induction motor (IM) drives, permanent magnet (PM) brushless DC (BLDC) motor drives, and switched reluctance motor (SRM) drives.

### A. *Brushed DC Motor Drives*

Brushed DC motors are well known for their ability to achieve high torque at low speed and their torque–speed characteristics suitable for the traction requirement. The motor speed is adjusted through varying voltage. Being suitable to propel a vehicle and easy to be controlled, they have been used on EVs. Brushed DC motors can have two, four or six poles depending on power output and voltage, and may have series or shunt field windings. On the one hand, shunt motors have the better controllability than series motors. Separately excited DC motors are inherently suited for field weakened operation, due to its decoupled torque and flux control characteristics. On the other hand, a range of extended constant power operation is obtained by separate field weakening.

However, brushed DC motor drives have a bulky construction, low efficiency, low reliability, and higher need of maintenance, mainly due to the presence of the mechanical commutator and brushes. It is difficult to downsize brushed DC motors. This makes brushed DC motors more heavy and expensive. Furthermore, friction between brushes and commutator restricts the maximum motor speed.

### B. *Induction Motor Drives*

Induction motors are of simple construction, reliability, ruggedness, low maintenance, low cost, and ability to operate in hostile environments.

The absence of brush friction permits the motors to raise the limit for maximum speed, and the higher rating of speed enable these motors to develop high output. Speed variations of induction motors are achieved by changing the frequency of voltage. Field orientation control (FOC) of induction motor can decouple its torque control from field control. This allows the motor to behave in the same manner as a separately excited dc motor. This motor, however, does not suffer from the same speed limitations as in the dc motor. Extended speed range operation beyond base speed is accomplished by flux weakening, once the motor has reached its rated power capability. A properly designed induction motor, e.g., spindle motor, with field oriented control can achieve field weakened range of 3-5 times the base speed [4].

However, the controllers of induction motors are at higher cost than the ones of DC motors. Furthermore, the presence of a breakdown torque limits its extended constant-power operation. At the critical speed, the breakdown torque is reached. Generally, for a conventional IM, the critical speed is around two times the synchronous one. Any attempt to operate the motor at the maximum current beyond this speed will stall the motor. Although FOC may extend constant power operation, it results in an increased breakdown torque thereby resulting in an over-sizing of the motor. In addition, efficiency at a high speed range may suffer in addition to the fact that IMs efficiency is inherently lower than that of permanent magnetic (PM) motors and switched reluctance motors (SRMs) due to the absence of rotor winding and rotor copper losses.

### *C. Permanent Magnet Brushless DC Motor Drives*

PM BLDC motor drives are specifically known for their high efficiency and high power density. Using permanent magnet, the motors can eliminate the need for energy to produce magnetic poles. So they are capable of achieve higher efficiency than DC motors, induction motors and SRMs. Furthermore, heat is efficiently dissipated to the surroundings. The speed range may be extended three to four times over the base speed if for a PM BLDC motor a conduction-angle control is used [3].

PM BLDC motor drives have the other drawbacks in that the magnet is expensive and that the mechanical strength of the magnet makes it difficult to build a large torque into the motor. PM BLDC motors have no brush to limit speed, but questions persist over the fixing intensity of the magnet because it restricts the maximum speed if the motors are of an inner-rotor type. Furthermore, this motor suffers from a rather limited field weakening capability. This is due to the presence of the PM field which can only be weakened through production of a stator field component which opposes the rotor magnetic field. Nevertheless, extended constant power operation is possible through the advancing of the commutation angle.

### *D. Switched Reluctance Motor Drives*

SRM drives are gaining much interest and are recognized to have a potential for EV applications. These motor drives have definite advantages such as simple and rugged construction, fault-tolerant operation, simple control, and outstanding torque–speed characteristics. SRM drives can inherently operate with an extremely long constant-power range.

The torque-speed characteristics of SRM drives match very well with the EV load characteristics. The SRM drive has high speed operation capability with a wide constant power region. The motor has high starting torque and high torque-inertia ratio. The rotor structure is extremely simple without any windings, magnets, commutators or brushes. The fault-tolerance of the motor is also extremely good. Because of its simple construction and low rotor inertia, SRM has very rapid acceleration and extremely high speed operation. Because of its wide speed range operation, SRM is particularly suitable for gearless operation in EV propulsion [5]. In addition, the absence of magnetic sources (i.e., windings or permanent magnets) on the rotor makes SRM relatively easy to cool and insensitive to high temperatures. The latter is of prime interest in automotive applications, which demand operation under harsh ambient conditions. An extended range of 2-3 times the base speed is usually possible using an appropriate control [4].

The disadvantages of SRM drives are that they have to suffer from torque ripple and acoustic noise. However, these are not potential problems that prohibit its use for EVs application.

### *E. Comparisons*

In order to obtain the most appropriate choice for EVs among four types of motor drives, some publications give their contributions [1]-[11]. From the above summarized features of four types of motor drives for EVs, Table I lists weight factors in efficiency, weight, and cost of four types of motor drives, where 5 marks represent the highest efficiency, lowest weight, and lowest cost, respectively.

TABLE I
COMPARISONS BETWEEN FOUR TYPES OF ELECTRIC MOTOR DRIVES

| 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 |

The above table indicates that DC motor drives will continue to be used in EVs because DC motor drives are available at the lowest cost. From the point of view of efficiency, PM BLDC motor drives are the best choice. SRM drives have the lowest weight among four types of motor drives for EVs. If the choice of motor drives for EVs is determined by three factors that are weight, efficiency and cost, it is clear that SRM drives are the best choice for EVs. Except for the efficiency, weight and cost, SRM drives also have the ascendancy in the aspects of cooling, maximum speed, fault tolerance, and reliability.

In an SRM, the phase windings on the stator in turn set up a magnetic dipole between stator and rotor poles. The resulting tendency is to reduce the air-gap reluctance. It results in that the rotor pole moves toward an aligned position with an excited stator pole. This operational feature is much different than the electromechanical energy conversion that takes place in DC motors, IMs or PM BLDC motors, which depend on rotor windings or magnets on the rotor in order to establish proper magnetomotive force (mmf) in the air-gap. Flux sources on the rotor typically have features, such as winding resistance or the flux density of the permanent magnets, which are strongly affected by temperature. It will result in a considerable amount of thermal coupling and, therefore, heat transfer into the rotor. However, heat generated due to both copper loss and iron loss in the core of the SRM is principally in the stator. Thus, one additional benefit to SRM drives is that it is easily cooled. However, it can be a potential problem to DC motor drives, IM drives and PM BLDC motor drives because their control performances are functions of temperature and their rotor structures. Furthermore, SRMs typically have a low-cost construction due to the absence of windings and permanent magnets on the rotor structure. This is of prime interest for EVs.

A ratio of maximum speed to base speed can reach to 5~6 and yields a minimum power rating for a maximized acceleration performance and regenerative braking capability. SRM drives are known to be capable of high-speed operation over a wide constant power region. Since high-speed operation, typically more than 10,000 rpm, is necessary, SRM drives are capable of fulfilling this criteria naturally. PM BLDC motor drives, inversely, must have rotor modifications that result in degraded performance/cost in order to operate in this range of speed. As for IM drives, their maximum speed is generally smaller than 10,000 rpm. Hence, PM BLDC and IM drives are limited to lower ranges.

Fault tolerance is also an important issue and desirable feature in EVs. Typically, when a component fails it is desired to have a certain amount of redundancy built into an EV such that the EV can still operate until maintenance can be performed. However, in order to yield this redundancy, cost becomes exorbitant. It is excited that SRM drives are naturally fault tolerant. For IM and PM BLDC motor drives, their electromechanical energy conversion is interdependent upon proper excitation. Conversely, SRM drives have discrete phase windings and thus phase windings are independent of each other. Consequently, in an SRM drive if one phase fails the SRM drive can still operate at a somewhat degraded performance until repairs can be conducted. Additionally, the converter topology used for an SRM protects it from serious electrical fault of shoot-through, which is not eliminated fully in IM and PM BLDC motor drives.

In aspect of safety and reliability, in addition, SRM drives may be superior to other three types of motor drives. Hence, SRM drives are suitable for many EVs applications where safety and reliability are of key importance or hazardous atmospheres prevail.

In summary, after evaluating tradeoffs between the efficiency, weight and cost, cooling, maximum speed, fault tolerance, safety and reliability for brushed DC motor drives, IM drives, PM BLDC motor drives, and SRM drives, SRM drives are the most appropriate candidate by evaluating an optimal balance of these criteria.

## V. CONCLUSIONS

In this study, six types of the drivetrain systems of electric motor drives for EVs have been discussed. The drivetrain schemes with the single-level reduction gear are well suitable for electric motor drives with wide speed range and highly maximum speed in EVs. Furthermore, the main requests of EVs on electric motor drives and expected output characteristics of electric motor drives are presented in this paper.

The comparative investigation in the efficiency, weight, cost, cooling, maximum speed, and fault-tolerance, safety, and reliability has been accomplished for SRM, IM, PM BLDC, and brushed DC motor drives. To be specific, a) In the aspect of efficiency, PM BLDC motor drives are better than SRM drives, IM drives and brushed DC motor drives; b) The weight of SRM drives is lower than PM BLDC motor, IM, and brushed DC motor drives; c) Brushed DC motor drives have the lowest cost for these four types of motor drives; d) Taking into account the aforementioned three criteria, SRM drives are superior to other three types of motor drives. Furthermore, SRM drives also have the ascendancy in the aspects of cooling, maximum speed, fault tolerance, safety, and reliability. Therefore, SRM drives are ideally suitable for nowadays EV applications.

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