IJEES

International Journal of Electrical Engineering and Sustainability (IJEES)

ISSN (online): 2959-9229

https://ijees.org/index.php/ijees/index

Volume 1 | Number 2 | April-June 2023 | Pages 21-28

Research Article

Recent Trends and Challenges of Electric Motor Technologies

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Received: March 17, 2023 Accepted: May 25, 2023 Published: June 5, 2023

Abstract: The growing popularity of electric vehicles (EVs) is being interpreted as a natural progression towards better technology in the automotive industry. This necessitates a thorough examination of the engine, which is the beating heart of these EVs. An electric vehicle's motor is a critical part of the vehicle's propulsion system, with the capacity to affect the vehicle's efficiency, weight, cost, dependability, power output, and performance. As a result, there is a pressing need for comprehensive comparison research that evaluates and contrasts the many motor types and topologies now in use. The capabilities of DC motors, induction motors, switching reluctance motors, permanent magnet AC motors, and permanent magnet DC motors, all of which can be employed for electric vehicle propulsion, are discussed. Recommendations for various novel designs of brushless DC motors are offered, along with a comprehensive assessment of current motors and the potential use of power electronic approaches to EVs. Motors with permanent magnets can be either a permanent magnet hybrid or a permanent magnet spoke or insert motor.

Keywords: Electric Motor; Electrical Vehicles; DC Motor; Induction Motor; Permanent Magnet Synchronous

1. Introduction

Many reasons have contributed to the growing preference for electric vehicles. EVs have a significant efficiency advantage over their fossil fuel counterparts from the power plant. Better torque-speed capabilities, the ability to function without any gearbox, inexpensive maintenance, and emissions-free and silent operation are just a few of the explanations why EVs are becoming increasingly popular. When powered by renewable energy sources like solar, hydro, wind, etc., these automobiles are also considered environmentally friendly. As a result, EVs are considered the wave of the future [1,2].

There have been three significant periods in the development of EVs. In the early 20th century, electric motors were as common as vehicles fueled by steam or internal combustion engines. Long trips were uncommon, therefore electric cars' limited range wasn't a big deal back then. Porsche developed the first hybrid EV in 1989 [2]. The goal was to increase the internal combustion engine's (ICEs) productivity by using it in conjunction with an electric traction motor. In terms of power conversion plus motor control, a lot of new ground was broken with the advent of power electronics. Because of this, electric cars are making a comeback. Electric vehicles were unable to compete with those powered by ICE due to their low power density and expensive cost of batteries. These days, electric and hybrid electric vehicles are making a comeback to the market because of improvements in battery technology, motor efficiency, and power conversion efficiency [3,4].

Motors for electric vehicles are significantly different from those utilized in other contexts. These motors have requirements that must be met and must be in sync with the vehicle's traction effort. Furthermore, the weight of these motors must exceed a certain limit because it directly correlates to the driving range. The ideal characteristics of an electric traction motor maximize productivity, high power density, regenerative brakes, durability in extreme environments, cost of repair, and dependability. Battery electric vehicles and hybrid electric vehicles dominate the market. Brushless DC motors (also known as permanent magnet DC motors) are becoming increasingly popular for such vehicles.

2. Motor Topologies

In today's electric vehicles, you may find a wide variety of electric motors. A wide variety of motor topologies, each with its own set of requirements, can be employed to propel an EV. As a result, there are several types of DC motors, induction motors, brushless alternating current (BLAC) motors, and brushless direct current (BLDC) motors available in different markets [6]. The speed and power ratings of variable-speed motors are not considered to be "nominal". The motor's design is a balancing act between portability and performance. Typically, motors have lower ratings than their maximum power output. From a few kilowatts for electric cycles up to 200 kilowatts for electric cars, the peak power capability of a motor can range widely. The strength of the machine is mostly determined by consumer demand. Power-speed efficiency maps and power output-speed performance maps can both be used to describe the performance rating of a variable-speed motor. According to the kind of electric motor, efficiency decreases when operating points are outside of the ideal region. The performance of a traction motor is determined by the various working points applied to it throughout each driving cycle. Thereby, a motor's design defines its performance throughout a broad range of speeds and powers. The input voltage plays a role in a motor's efficiency as well. Machines with a higher voltage rating are more efficient by design [7,8]. The efficiency of a motor drops significantly when it is run at voltages below its rated voltage. This is more prevalent at a low-charge state.

3. Motor Characteristics

Electric vehicles (EVs) are powered by electric motors, which differ from traditional internal combustion engines (ICEs) in several key ways. One of the most significant differences is in their motor characteristics. Electric motors are highly efficient and can generate high levels of torque at low speeds, making them well-suited for use in vehicles. They also have a more linear power delivery compared to ICEs, which means that the torque is available even at low speeds. Additionally, electric motors have fewer moving parts than ICEs, resulting in less maintenance and longer lifetimes. Another important characteristic of EV motors is their regenerative braking system, which recaptures energy that would otherwise be lost during braking and stores it in the vehicle's battery [9-11]. This feature not only improves the vehicle's efficiency but also reduces wear on the vehicle's brake pads. Overall, the motor characteristics of EVs make them a promising alternative to traditional ICE vehicles, offering high efficiency, low maintenance, and improved performance. The scientific literature defines the primary needs for an electric vehicle's drivetrain as follows:

- A manageable cost.
- Extremely high peak power and power density.
- Both provide plenty of power at rapid speeds for cruising and a great of torque at low speeds for beginning and climbing.
- Quickly resolving torque issues.
- High operating speeds, with no loss of torque or output power.
- Excellent performance over a broad spectrum of speeds and torque.
- Extreme dependability and toughness in all sorts of driving situations and
- Outstanding results in regenerative braking.

Similar characteristics can also be seen between the traction attempt and the properties of electric motors concerning velocity. The constant torque sector is quite small at slower speeds, while the constant power region is relatively large at high speeds. This profile is based on the fundamental features of the energy supply and transmission. The profile of traction effort versus speed for any given source of electric vehicle propulsion must always consist of a constant torque zone followed by a constant power area concerning speed.

4. Comparative Study

A. DC motors

Brushed DC motors are well-liked because of their manageability and great torque at low speeds. They excel in a traction setting but are not suited for EVs in terms of torque-speed characteristics. The key benefits of these motors are their inexpensive price, proven technology, straightforward yet effective control, and dependability. Once widely used as traction motors, they have since given way to AC motors like induction and synchronous motors, made possible by improvements in power electronics. This is because extremely efficient and adjustable inverters have replaced the commutator in DC motors to perform the inversion of current [12-14]. These motors' primary drawbacks are their poor power density, inefficiency, and frequent coal brush repairs (every 3000 h). DC motors are extremely costly because their size cannot be reduced without significant effort. In addition, the friction created by the brushes and the commutator limits the maximum speed of the motor. It is the rate at which the motor arrives at breakdown torque boundaries. Breakdown torque causes the motor to stall if it is operated at speeds above the critical speed and maximum current. So, the constant power operation is constrained by the motor's breakdown torque. The constant power area expands with increasing breakdown torque.

B. Vector control of induction motors

The induction motor driving benefits most from the vector control approach when it comes to improving its dynamic efficiency. By using vector control, the torque control of IMs may be separated from the field control. To enable instantaneous torque control of the induction motor, this calls for line-coordinate transformations. To do this, direct torque control is used. Torque and flux hysteresis control, an optimal switching vector lookup table, and a motor model are the three components that make up direct torque control. The motor model uses data from the two stator phases and the battery voltage to make predictions about the produced torque, the stator flux, and the shaft speed. The primary drawbacks of DC motors are their low power density, the need for regular maintenance of the coal brush (approximately every 3000 h), and their low efficiency [15]. DC motors are also cumbersome and expensive because they are difficult to miniaturize; furthermore, their top speed is limited by friction between the brushes and the commutator.

C. Induction motors

Induction motors are the most mature technology amongst the various commutator-less motor drives. The squirrel cage-type induction motors are the most acceptable motors for use in electric propulsion. They have advantages such as reliability, low maintenance, low cost and robustness [16]. The critical speed of an induction motor is around twice the synchronous speed and can be written as Eq. (1).

$$N_c = 2 * N_s \tag{1}$$

Where N_c represents the critical speed in rpm and N_s shows the synchronous speed of the machine in rpm.

At this rpm, the motor's maximum torque is reached. At speeds over the critical speed and maximum current, the motor will start to stall due to the breakdown torque. therefore, the motor's breakdown torque limits how much consistent power may be output. the constant power area expands in proportion to the square of the value of the breakdown torque.

D. Vector control of induction motors

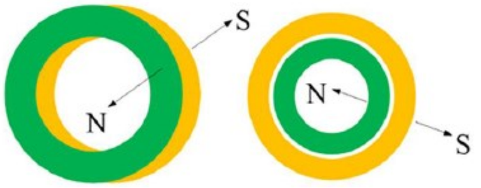
The induction motor drive benefits most from the vector control technique when it comes to improving its dynamic performance. By using vector control, the torque control of IMs may be separated from the field control. To enable instantaneous torque control of the induction motor, this calls for line-coordinate transformations [17-19]. To do this, direct torque control is used. Torque and flux hysteresis control, an optimal switching vector lookup table, and a motor model are the three components that make up direct torque control. The motor model uses data from the two stator phases and the battery voltage to make estimates about the produced torque, the stator flux, and the shaft speed.

E. *Multiphase pole - changing IM drive*

The number of poles in an induction machine can be altered in two basic ways. The first method calls for a customized induction motor. Altering the stator's pole count involves rearranging the windings' coils. The second method also calls for a customized piece of equipment. Figure 1, shows flux orientation in axial and radial flux motors. Figure 2, indicates the basic idea showing the dual-inverter control scheme: inverter only takes care of the reactive voltage component. Figure 3, presents the design of single- and double-sided axial-flux induction motors. Figure 4, demonstrates the main flux of a pole-changing IM drive. There are two stator windings in this motor. One winding is employed for low-speed operations, while the other is used for high-speed ones. The induction motor's synchronous speed decreases as the number of poles increases as indicated in Eq. (2) [20-23].

$$N_s = \frac{120 * f}{P} \Rightarrow N_s \propto \frac{1}{p} \tag{2}$$

where N_s represents the speed of the induction motor in rpm, f indicates the frequency of supply in H_z and P shows the number of poles of the machine.



Axial Flux Orientation Radial Flux Orientation

Figure 1. Flux orientation in axial and radial flux motors [23].

The critical speed is roughly double the synchronous speed, hence increasing the former will end up resulting in the latter. As a consequence, the motor's constant power region has grown, as has the breakdown torque, which is proportional to the critical speed. Because of this, increasing the speed while decreasing the number of poles is possible with multiphase pole-changing drives. A pole-switching squirrel-cage induction motor with six phases is described. To achieve phase reversal between the two carriers of the six-phase inverter during four-pole operation, a novel sinusoidal pulse width modulation (PWM) method is proposed. Odd multiples of the carrier frequency, which are the focus of the DC link harmonics, can be removed with the help of double Fourier series. By lowering the DC link harmonic currents, this innovative PWM approach can extend the useful life of batteries.

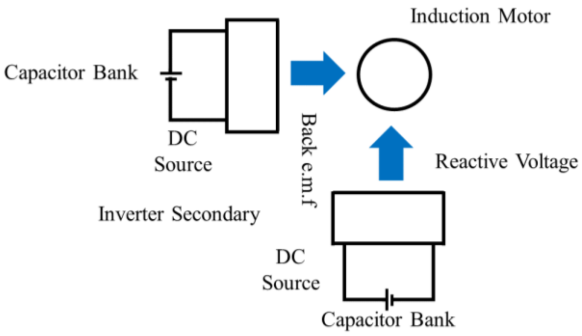
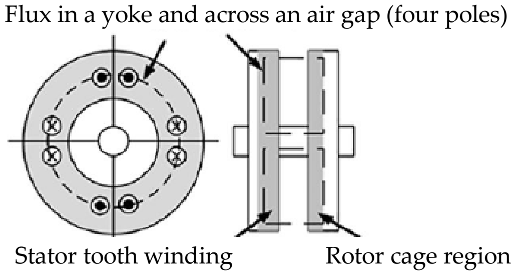
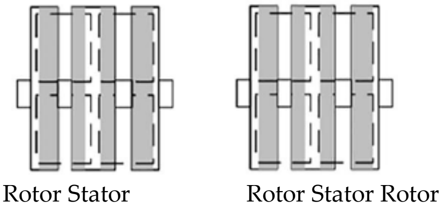


Figure 2. Basic idea showing the dual-inverter control scheme [24].



i) Single side machine



ii) Double side machine

Figure 3. Design of single- and double-sided axial-flux induction motors [25].

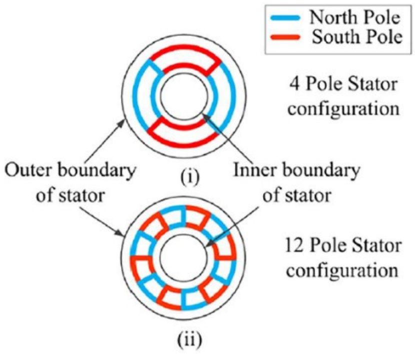


Figure 4. Main flux of a pole-changing IM drive [26].

F. *Permanent magnet synchronous (PMS) motors (or brushless AC)*

Another variety of AC motors utilized for propulsion in electric vehicles is the brushless variety. Numerous automakers have incorporated this system into their vehicles. When a sinusoidal AC is delivered to these motors, a sinusoidal field is generated. Torque is continuous and smooth because of the interaction between the sinusoidal field and current. This characteristic sets BLAC motors apart from their BLDC counterparts. In contrast, the rectangular currents used to power brushless DC motors result in a rectangular field [27,28]. Compared to the torque generated by a sinusoidal field and current, the torque generated by a rectangle-shaped field and flow interaction is larger, but it is not a smooth sine wave. The benefits of BLAC motors include increased efficiency, greater power density, and more effective heat dissipation. These motors are built to withstand extreme conditions thanks to their improved heat dissipation. These motors only have a small constant power range, which is a major drawback. The constant power zone needs to be sufficiently large to support increased velocities. Therefore, power converters that can increase the speed range beyond the base speed are required. These converters serve to increase the efficiency of the motors by controlling the conduction angle at higher speeds [29,30].

G. *Switched reluctance motor*

As an alternative to conventional electric traction motors, switching reluctance motors have recently entered the market. This is mostly because of the increasing anxiety surrounding magnetism-related substances. The prominent poles on the motor's rotor are its defining feature. Torque production in these motors occurs due to the difference in synchronous reluctance between the direct axis and the quadrature axis, as there is no excitation field in the rotor. The rotor is inexpensive, durable, and temperature indifferent. The reluctance motor's peak efficiency is similar to that of the induction motor, and it maintains a high level of efficiency over a wide range of speeds. Hybrid switching reluctance motors can achieve efficiencies exceeding 95% [31,32].

This type of motor's merits includes its straightforward design, high reliability, fault tolerance, ease of operation, and excellent torque-speed characteristics. The huge constant power zone is where the switching reluctance motor shines. Other motors tend to have this limitation by design, so power electronics or other methods are used to increase it. In addition to these benefits, the high rotor inductance ratio facilitates the implementation of senseless control. When compared to other motor types, switched reluctance motors have the added benefit of being simple to cool. This is helpful once more since it allows for operation in severe environmental conditions. Despite its many benefits, the switching reluctance motor is not widely employed in electric cars. High acoustic noise is produced as a result of the high torque ripple, the requirement of a specific converter topology, the excessive bus current ripple, and the development of electromagnetic interference noise. Nonetheless, despite their drawbacks and benefits, EVs have many uses that necessitate them [33-35].

5. Conclusion

According to the traction profile of an electric vehicle (EV), DC motors are among the finest options. They are both straightforward and sturdy, making for great torque and speed characteristics. These motors have a low power density and need regular maintenance. Induction motors are simple to use, reliable, and low maintenance because of their flux-weakening features. The constant power region of these motors is limited by their breakdown torque. When running at high speeds, their efficiency is low and their power factor is low. When applied to induction motors, vector control enhances both the motor's dynamic performance and its constant power region.

Since low-speed and high-speed operations require different windings, pole-changing induction motors can function efficiently at both. The power factor of high-speed induction motors can be improved with the help of a dual-converter method. Lightweight and with superior mechanical qualities and dynamic performance, axial flux induction motors are becoming increasingly popular. Due to this, they are usable in low- to medium-speed applications. These modern improvements to the induction motor make the motor better in certain ways but come at a higher price and larger size.

Brushless AC motors, also known as permanent magnet synchronous motors, are the other form of alternating current (AC) motor. Their power density, efficiency, smooth torque, and environmental heat dissipation are all superior. Because of the lack of a large constant power region, power converters are required for their use. Another kind of synchronous motor is the switching reluctance motor. In comparison to brushless AC motors, these have the best features for use in an electric vehicle, including a large constant power region. However, these motors produce audible noise due to torque ripple. They also have a high level of current ripple.

Due to their excellent power density and torque characteristics, brushless DC motors have been increasingly popular in recent years. A lot of work has gone into and is being put into perfecting these motors. As a result, many variations of brushless DC motors have emerged. While this motor is an excellent option, its limited flux weakening capabilities prevent it from providing an expansive constant power region. Designs, whereby the rotor length is limited, can benefit from the usage of axial flux BLDC motors. When compared to axial flux motors, radial flux motors have fewer copper losses. Losses in the radial flux motor approach those of the single air gap slotted type axial motor, which has the lowest total losses, as its peak power increases. At any given output level, the fundamental benefit of axial flux motors is their exceptionally high power per unit active volume.

When considering permanent magnet mounting, inside permanent magnet motors outperform their surface-mounted counterparts in terms of overload capacity. Recently introduced to the market are "spoke motors," where the permanent magnets are laid out in the shape of spokes. These motors outperform standard SPM motors in terms of back EMF and torque value, and they have a high power density per unit of active volume. These motors have a greater resistance to demagnetization from external fields thanks to their flux barrier-type rotor design. A new permanent magnet motor that combines features of SPM and IPM motors has been developed. This motor displays the qualities of both SPM and IPM motors while having fewer drawbacks than SPM motors. A variation on the BLDC motor, the permanent magnet inset motor has the PM magnets embedded into the rotor. This motor benefits from the combined use of PM torque and reluctance torque.

Author Contributions: All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgements: We would like to express our deepest gratitude to Karabuk University for providing us with the necessary resources and facilities to conduct our article. Their unwavering support and guidance have been instrumental in the successful completion of this article.

Conflicts of Interest: The authors declare no conflict of interest.

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