

Electric Motors in Electric Vehicles: A Comprehensive Review

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Abstract—Electric vehicles (EVs) have emerged as a key solution to reduce greenhouse gas emissions and dependence on fossil fuels, driving significant advancements in electric motor technologies. This paper presents a comprehensive review of electric motors used in EV applications, focusing on their design, performance characteristics, control strategies, and suitability for various vehicle requirements. Major motor types such as Permanent Magnet Synchronous Motors (PMSM), Induction Motors (IM), Brushless DC Motors (BLDC), and Switched Reluctance Motors (SRM) are analyzed in terms of efficiency, power density, torque characteristics, cost, and reliability. The study also examines recent developments in motor control techniques, including field-oriented control and direct torque control, which enhance dynamic performance and energy efficiency. Furthermore, emerging trends such as advanced materials, thermal management, and integration with power electronics are discussed. Comparative analysis highlights the advantages and limitations of each motor type, providing insights for optimal motor selection in different EV applications. The review concludes by identifying future research directions aimed at improving motor efficiency, reducing cost, and enhancing overall EV performance.

Index Terms—Electric Vehicles (EVs), Permanent Magnet Synchronous Motor (PMSM), Induction Motor (IM), Brushless DC Motor (BLDC), Switched Reluctance Motor (SRM), DC Motor, Motor Control, Power Density, Efficiency.

I. INTRODUCTION

The rapid depletion of fossil fuel resources and the growing concern over environmental pollution have accelerated the global transition toward sustainable transportation systems. Electric Vehicles (EVs) have emerged as a promising alternative to conventional internal combustion engine (ICE) vehicles due to their

potential to reduce greenhouse gas emissions, improve energy efficiency, and decrease dependence on non-renewable energy sources. Governments, industries, and research Institutions worldwide are increasingly investing in EV technologies to meet stringent emission regulations and promote clean mobility.

A critical component that determines the performance, efficiency, and reliability of an EV is its electric motor. Unlike ICE vehicles, where mechanical complexity dominates, EVs rely heavily on electric propulsion systems, where the motor plays a central role in converting electrical energy into mechanical power. The selection of an appropriate motor significantly impacts key vehicle parameters such as acceleration, torque delivery, energy consumption, driving range, and overall system cost. Various types of electric motors have been employed in EV applications, each offering distinct advantages and limitations. Among them, Permanent Magnet Synchronous Motors (PMSMs) are widely favored for their high efficiency and power density, while Induction Motors (IMs) are known for their robustness and cost-effectiveness. Brushless DC (BLDC) motors provide good efficiency and controllability, whereas Switched Reluctance Motors (SRMs) are gaining attention due to their simple construction and fault tolerance. The choice of motor depends on multiple factors, including performance requirements, cost constraints, thermal characteristics, and control complexity.

In addition to motor selection, advanced control strategies such as Field-Oriented Control (FOC) and Direct Torque Control (DTC) play a vital role in enhancing the dynamic response and efficiency of EV propulsion systems. Recent advancements in power electronics, battery technologies, and digital control systems have further contributed to the evolution of electric motor drives in EVs.

This paper presents a comprehensive review of electric motors used in electric vehicles, focusing on their operating principles, performance characteristics, advantages, and limitations. A comparative analysis of different motor types is provided to assist in optimal motor selection for various EV applications. Furthermore, emerging trends and future research directions in electric motor technology are discussed to highlight the ongoing developments in this rapidly evolving field.

The remainder of this paper is organized as follows: Section II discusses the classification and working principles of electric motors used in EVs. Section III presents a comparative analysis of different motor types. Section IV explores control strategies and technological advancements. Section V highlights current challenges and future research directions, followed by conclusions in Section VI.

II. PERMANENT MAGNET SYNCHRONOUS MOTOR

2.1. Working Principle

The Permanent Magnet Synchronous Motor (PMSM) is one of the most widely used motors in electric vehicle (EV) applications due to its high efficiency and superior performance characteristics. In a PMSM, permanent magnets are embedded or mounted on the rotor, eliminating the need for external rotor excitation. The stator consists of three-phase windings similar to those in conventional AC machines.

When a three-phase AC supply is applied to the stator windings, a rotating magnetic field is produced. The magnetic field generated by the stator interacts with the constant magnetic field of the rotor magnets, resulting in electromagnetic torque. The rotor rotates synchronously with the stator field, meaning there is no slip between them. This synchronous operation ensures precise speed control and improved efficiency. PMSMs are generally classified into two types: Surface-Mounted PMSM (SPMSM) and Interior PMSM (IPMSM). The IPMSM configuration is particularly preferred in EVs due to its capability for flux weakening, which enables operation over a wide speed range.

2.2. Motor Control Techniques

Efficient control of PMSMs is essential to achieve optimal performance in EV applications. Advanced

control strategies are employed to regulate torque, speed, and current while maintaining high efficiency. One of the most commonly used techniques is Field-Oriented Control (FOC), also known as vector control. FOC transforms the stator currents into a rotating reference frame, allowing independent control of torque and flux components, similar to a DC motor. This results in smooth torque production and a fast dynamic response.

Another control strategy is Direct Torque Control (DTC).

III. BLDC (BRUSHLESS DC MOTOR)

3.1. Working Principle

The Brushless DC Motor (BLDC) is widely utilized in electric vehicle (EV) applications due to its high efficiency, compact size, and excellent controllability. Unlike conventional brushed DC motors, BLDC motors eliminate mechanical brushes and commutators, thereby reducing maintenance requirements and improving reliability. A BLDC motor consists of a stator with three-phase windings and a rotor embedded with permanent magnets. The operation of a BLDC motor is based on electronic commutation, where power electronic switches are used to energize the stator windings in a specific sequence.

When the stator windings are energized, a rotating magnetic field is generated, which interacts with the magnetic field of the rotor magnets to produce torque. The commutation process is controlled using rotor position information obtained from sensors such as Hall-effect sensors or through sensor less techniques. The rotor follows the stator magnetic field, resulting in continuous rotation. BLDC motors typically operate with trapezoidal back electromotive force (EMF) waveforms, which distinguishes them from PMSMs that generally exhibit sinusoidal back EMF characteristics.

3.2. Motor Control Techniques

Efficient control of BLDC motors is essential for achieving high performance in EV applications. The most common control strategy is electronic commutation using a six-step (trapezoidal) control method, where the inverter energizes two phases at a time while the third phase remains unpowered.

Rotor position detection is critical for proper

commutation. This is typically achieved using Hall-effect sensors placed within the motor. Alternatively, sensor less control techniques based on back EMF detection are employed to reduce cost and improve system reliability. For improved performance, advanced control techniques such as Field-Oriented Control (FOC) can also be applied to BLDC motors, enabling smoother torque production and reduced torque ripple. Pulse Width Modulation (PWM) is commonly used to regulate the voltage applied to the motor, thereby controlling speed and torque efficiently.

3.3. Power Density

BLDC motors offer high power density due to the use of permanent magnets and efficient electromagnetic design. The absence of brushes reduces mechanical losses and allows for higher-speed operation.

The compact structure of BLDC motors makes them particularly suitable for applications where space and weight are critical factors, such as electric two-wheelers, e-bikes, and compact EVs. High torque-to-weight ratio and efficient heat dissipation further contribute to their superior power density. However, the reliance on permanent magnets increases material cost and may introduce challenges related to thermal demagnetization at high temperatures.

3.4. Efficiency

BLDC motors are known for their high efficiency, typically ranging from 85% to 95%. The elimination of brushes reduces frictional losses, while electronic commutation ensures efficient energy conversion.

Major losses in BLDC motors include stator copper losses, core losses, and switching losses in the inverter. Proper control of switching frequency and current can help minimize these losses. Efficiency can be further enhanced using advanced control strategies, optimal PWM techniques, and effective thermal management. As a result, BLDC motors contribute to improved energy utilization and extended driving range in EVs.

IV. SWITCHED RELUCTANCE MOTOR (SRM)

4.1. Working Principle

The Switched Reluctance Motor (SRM) is gaining increasing attention in electric vehicle (EV) propulsion systems due to its simple structure, high reliability, and absence of permanent magnets. The

SRM consists of a salient-pole stator with concentrated windings and a rotor made of laminated steel without windings or permanent magnets.

The operating principle of an SRM is based on the concept of reluctance torque. When a stator phase winding is energized, a magnetic field is produced that attracts the nearest rotor pole toward the stator pole, aligning the rotor in a position of minimum magnetic reluctance. As the rotor moves toward this aligned position, torque is produced. By sequentially energizing different stator phases using a power electronic converter, continuous rotation of the rotor is achieved. Since the rotor does not contain windings or magnets, it has a very simple and robust structure, allowing it to operate at high speeds and withstand harsh operating conditions.

4.2. Motor Control Techniques

Control of SRMs is achieved through electronic switching of stator phase currents using a dedicated power converter. Accurate control of the phase excitation timing is essential to ensure efficient torque production and minimize torque ripple.

One commonly used control strategy is current control, where the phase current is regulated to maintain the desired torque output. Another technique is angle position control, in which the stator phases are energized according to the rotor position.

Rotor position information is typically obtained using position sensors such as encoders or resolvers. However, sensor less control techniques have been developed to estimate rotor position based on flux linkage or inductance variation, reducing system complexity and cost. Advanced control methods, including torque ripple minimization techniques, are often implemented to improve performance and reduce acoustic noise, which is one of the main challenges associated with SRMs.

4.3. Power Density

SRMs offer competitive power density due to their ability to operate at high speeds and tolerate high temperatures. The absence of permanent magnets and rotor windings simplifies the rotor structure, allowing it to withstand high centrifugal forces and enabling compact designs.

Additionally, the simple construction reduces mechanical losses and improves thermal performance. However, compared to PMSMs, the power density of

SRMs may be slightly lower due to higher torque ripple and less efficient magnetic utilization. Despite these limitations, continuous improvements in motor design and control techniques are helping enhance the power density of SRMs for EV applications.

4.4. Efficiency

Switched reluctance motors can achieve high efficiency, typically ranging between 85% and 93%, depending on operating conditions and design parameters. The absence of rotor copper losses contributes to improved efficiency and reduced thermal stress.

However, SRMs experience other types of losses, including stator copper losses, core losses, and switching losses in the power electronic converter. Proper design of the magnetic circuit and optimized control strategies help minimize these losses. Efficiency can also be improved through optimal excitation timing, advanced converter topologies, and improved magnetic materials.

V. AC INDUCTION MOTOR

5.1. Working Principle

The Induction Motor (IM), also known as the Asynchronous Motor, is widely used in electric vehicle (EV) applications due to its rugged construction, reliability, and cost-effectiveness. Unlike permanent magnet synchronous motors, IMs do not require permanent magnets or separate rotor excitation.

An IM operates on the principle of electromagnetic induction. The stator consists of three-phase windings supplied with AC power, which produce a rotating magnetic field. This rotating field induces currents in the rotor conductors (typically arranged in a squirrel-cage structure) due to relative motion between the stator field and the rotor.

The interaction between the induced rotor currents and the stator magnetic field generates torque, causing the rotor to rotate. Unlike synchronous motors, the rotor speed in an IM is slightly lower than the stator's synchronous speed, and this difference is known as *slip*. Slip is essential for torque production in induction motors.

5.2. Motor Control Techniques

Efficient control of induction motors is crucial for

achieving high performance in EV applications. Since IMs exhibit nonlinear characteristics, advanced control strategies are required.

Field-Oriented Control (FOC) is widely used for IM drives. It decouples torque and flux components by transforming stator currents into a rotating reference frame, enabling precise control similar to that of DC motors. This results in smooth torque response and improved efficiency.

Direct Torque Control (DTC) is another popular technique, which directly controls torque and stator flux without the need for complex transformations. DTC offers faster dynamic response compared to FOC, but it may produce higher torque and current ripples.

In addition, sensor less control methods are commonly used in EV applications to estimate rotor speed and position eliminating the need for mechanical sensors. These methods improve system reliability and reduce overall cost.

5.3. Power Density

The power density of induction motors is generally lower than that of permanent magnet synchronous motors due to the absence of high-energy permanent magnets. However, IMs can still achieve competitive power density through optimized design and advanced cooling techniques.

The rotor structure of an IM, typically made of aluminum or copper bars, is simple and robust, allowing operation under high mechanical stress. Although the presence of rotor losses limits compactness, improvements in materials and thermal management have enhanced the power density of modern IMs. Induction motors are particularly suitable for applications where durability and reliability are prioritized over size and weight constraints.

5.4. Efficiency

Induction motors offer good efficiency, typically ranging from 85% to 93% depending on operating conditions and design. However, their efficiency is generally lower than that of PMSMs due to additional losses.

The major losses in IMs include stator copper losses, rotor copper losses (due to induced currents), core losses, and stray losses. Rotor losses are particularly significant, as they are directly related to slip.

Advanced control strategies such as FOC and

optimized inverter switching techniques help improve overall efficiency. Additionally, operating the motor near its rated load and minimizing slip can further enhance efficiency. Despite slightly lower efficiency, IMs are widely used in EVs due to their robustness, lower cost, and absence of rare-earth materials.

VI. DC MOTOR

6.1. Working Principle

The Direct Current (DC) motor is one of the earliest types of electric motors used in electric propulsion systems. DC motors operate based on the principle that a current-carrying conductor placed in a magnetic field experiences a mechanical force. This force produces rotational motion in the motor.

A typical DC motor consists of a stator that produces a magnetic field and a rotor (armature) carrying current through windings. The armature windings interact with the magnetic field generated by the stator, resulting in electromagnetic torque. Mechanical commutation is achieved using brushes and a commutator, which ensure that the current direction in the armature windings reverses periodically to maintain continuous rotation.

Due to the presence of brushes and a commutator, DC motors require periodic maintenance and may suffer from mechanical wear and sparking. Nevertheless, they provide simple operation and good speed control characteristics.

6.2. Motor Control Techniques

DC motors are relatively easy to control compared to AC motors. The speed of a DC motor can be controlled by adjusting the armature voltage, field current, or by varying the armature resistance.

One common method used in EV applications is Pulse Width Modulation (PWM), where a DC-DC converter regulates the average voltage applied to the motor. By

varying the duty cycle of the PWM signal, the motor speed and torque can be effectively controlled.

Closed-loop control systems are often implemented using feedback from speed sensors to maintain stable motor operation under varying load conditions. Although the control system is relatively simple, modern EV applications prefer brushless motors due to their improved reliability and reduced maintenance.

6.3. Power Density

The power density of DC motors is moderate compared to modern brushless motor technologies. The presence of mechanical components such as brushes and commutators limit the maximum operating speed and increases mechanical losses. Additionally, the need for proper insulation and cooling increases the overall motor size. As a result, DC motors generally have lower power density compared to PMSMs and BLDC motors. Despite this limitation, they are still used in low-power applications and educational or experimental EV systems due to their simplicity.

6.4. Efficiency

DC motors typically achieve efficiencies in the range of 75% to 90%, depending on their design and operating conditions. Losses in DC motors include copper losses in the armature windings, core losses, mechanical friction losses, and brush contact losses.

The friction between brushes and the commutator contributes to additional power loss and heat generation. Proper maintenance and optimized design can help reduce these losses and improve overall efficiency. Although DC motors provide reliable operation and straightforward control, their efficiency and durability are generally lower than modern brushless motor technologies used in contemporary EVs.

Table 1: Comparison of types of motors

Parameters	PMSM	BLDC	SRM	AC Induction Motor	DC Motor
Efficiency	Very High (90–96%)	High (85–95%)	High (85–93%)	High (85–93%)	Moderate (75–90%)
Power Density	High	High	Medium–High	Medium	Medium
Cost	High	Moderate	Low	Moderate	Low
Control Complexity	Moderate	Moderate	High	High	Low

Advantages	High efficiency, high torque density, compact size	High efficiency, compact design, low maintenance	Simple construction, high reliability, no magnets	Robust, reliable, no permanent magnets	Simple control, good starting torque
Limitations	Expensive magnets, rare-earth dependency	Torque ripple, requires electronic commutation	Torque ripple, acoustic noise	Rotor losses, slightly lower efficiency	Brush wear, maintenance required

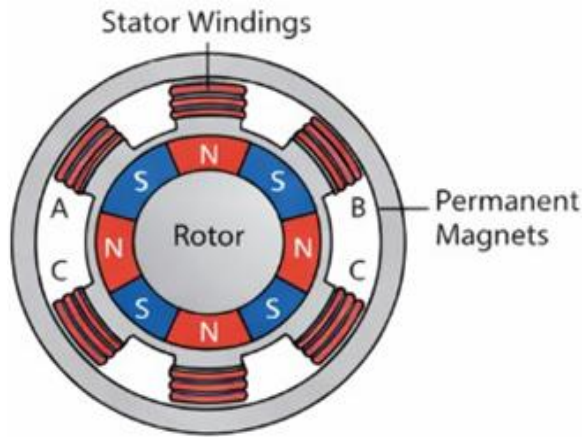


Fig.1. PMSM

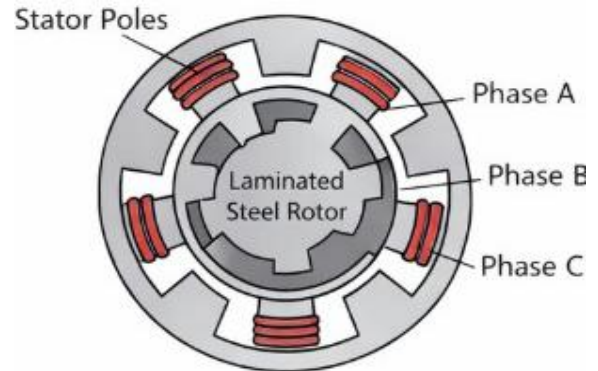


Fig. 4. SRM Motor

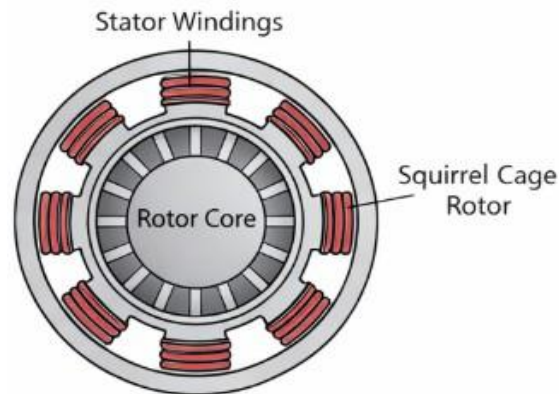


Fig. 2. AC Induction Motor

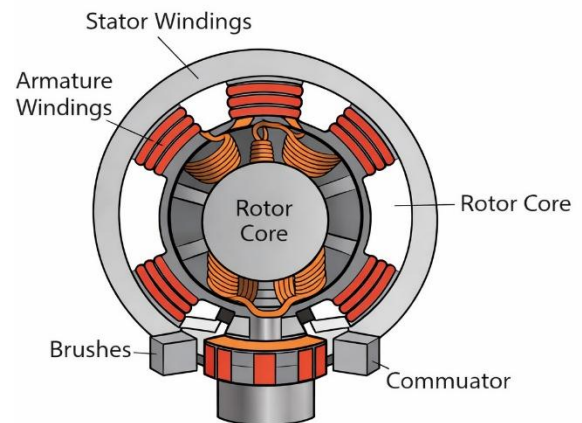


Fig. 5. DC Motor

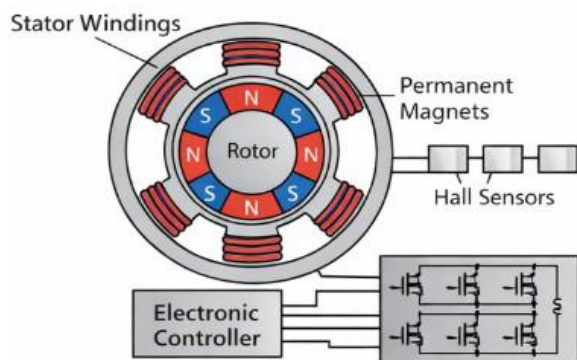


Fig. 3. BLDC Motor

VII. CHALLENGES AND FUTURE TRENDS

Despite significant advancements in electric motor technologies for electric vehicles (EVs), several technical and economic challenges still remain. These challenges must be addressed to further improve the performance, reliability, and affordability of EV propulsion systems.

One of the major challenges is the dependence on rare-earth materials, particularly in Permanent Magnet Synchronous Motors (PMSMs) and Brushless DC (BLDC) motors. Permanent magnets used in these motors often contain rare-earth elements such as

neodymium and dysprosium, which are expensive and subject to supply constraints. The fluctuating cost and limited availability of these materials can significantly impact the overall cost of EV production.

Another important challenge is thermal management. Electric motors in EVs operate under high load conditions and may experience significant heat generation due to copper losses, core losses, and inverter switching losses. Inefficient heat dissipation can reduce motor efficiency, affect insulation life, and decrease overall system reliability. Therefore, advanced cooling techniques and improved thermal design are essential for maintaining optimal motor performance.

Torque ripple and acoustic noise are also major concerns, particularly in Switched Reluctance Motors (SRMs) and some BLDC motor designs. These effects can lead to vibrations, reduced ride comfort, and increased mechanical stress on vehicle components. Research efforts are focused on improving motor design, control algorithms, and power electronic converters to minimize these issues.

Another challenge lies in the complexity of motor control systems. Modern EV motors require sophisticated control strategies such as Field-Oriented Control (FOC), Direct Torque Control (DTC), and sensor less control techniques. Implementing these control methods requires advanced digital controllers, precise sensors, and efficient power electronic converters, which increase system complexity and cost.

In addition, power density and efficiency optimization remain key research areas. EV manufacturers continuously seek motors that provide higher torque and power output while maintaining compact size and lightweight construction. Improving magnetic materials, motor topology, and winding configurations are important research directions to achieve these goals.

Looking toward the future, several technological trends are expected to shape the development of EV motors. One important trend is the development of rare-earth-free motor technologies, such as advanced induction motors and switched reluctance motors, to reduce dependence on expensive magnetic materials. Another promising direction is the integration of motor, inverter, and transmission systems into compact electric drive units, which can improve efficiency and reduce system weight. Advancements

in wide-bandgap semiconductor devices, such as silicon carbide (SiC) and gallium nitride (GaN), are also expected to enhance the performance of EV motor drive systems by improving switching efficiency and reducing power losses. Furthermore, the application of artificial intelligence and advanced control algorithms may enable more efficient motor operation, predictive maintenance, and improved energy management.

Overall, continuous research and technological innovations are essential to overcome existing challenges and enhance the performance, reliability, and cost-effectiveness of electric motors in future EV propulsion systems.

VIII. CONCLUSION

Electric vehicles (EVs) have emerged as a promising solution to address the growing concerns of environmental pollution, energy sustainability, and the depletion of fossil fuels. The electric motor serves as the core component of the EV propulsion system, directly influencing vehicle performance, efficiency, reliability, and driving range. Therefore, the selection and optimization of motor technologies are crucial for the successful development of efficient electric transportation systems.

This paper presented a comprehensive review of various electric motors used in EV applications, including Permanent Magnet Synchronous Motors (PMSM), Induction Motors (IM), Brushless DC Motors (BLDC), Switched Reluctance Motors (SRM), and conventional DC Motors. The working principles, motor control techniques, power density, and efficiency characteristics of each motor type were analyzed and discussed. A comparative study highlighted the advantages and limitations of these motors in terms of performance, cost, complexity, and suitability for different EV applications.

Among the reviewed motor technologies, PMSMs and BLDC motors demonstrate superior efficiency and power density, making them widely used in modern electric vehicles. Induction motors offer advantages such as robustness, reliability, and independence from rare-earth materials, while SRMs present a promising alternative due to their simple construction and fault tolerance. Conventional DC motors, although historically significant, are gradually being replaced by brushless motor technologies due to maintenance requirements and lower efficiency.

Furthermore, the paper discussed key challenges associated with EV motors, including dependence on rare-earth materials, thermal management issues, torque ripple, and the complexity of control systems. Emerging trends such as rare-earth-free motor designs, advanced power electronic converters, improved magnetic materials, and intelligent control algorithms are expected to significantly enhance the performance and reliability of future EV propulsion systems. In conclusion, continued research and innovation in motor design, materials, and control technologies will play a vital role in improving the efficiency, affordability, and sustainability of electric vehicles. These advancements will contribute significantly to the global transition toward cleaner and more energy-efficient transportation systems.

REFERENCES

- [1] C. C. Chan, "The state of the art of electric, hybrid, and fuel cell vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 704–718, Apr. 2007.
- [2] J. Larminie and J. Lowry, *Electric Vehicle Technology Explained*, 2nd ed. Chichester, U.K.: Wiley, 2012.
- [3] I. Husain, *Electric and Hybrid Vehicles: Design Fundamentals*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2011.
- [4] S. Ehsani, Y. Gao, and A. Emadi, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory and Design*, 2nd ed. Boca Raton, FL, USA: CRC Press, 2010.
- [5] T. M. Jahns and V. Blasko, "Recent advances in power electronics technology for industrial and traction machine drives," *Proceedings of the IEEE*, vol. 89, no. 6, pp. 963–975, Jun. 2001.
- [6] B. K. Bose, *Modern Power Electronics and AC Drives*. Upper Saddle River, NJ, USA: Prentice Hall, 2002.
- [7] R. Krishnan, *Permanent Magnet Synchronous and Brushless DC Motor Drives*. Boca Raton, FL, USA: CRC Press, 2010.
- [8] P. Vas, *Sensorless Vector and Direct Torque Control*. Oxford, U.K.: Oxford University Press, 1998.
- [9] A. Emadi, K. Rajashekara, S. S. Williamson, and S. M. Lukic, "Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations," *IEEE Transactions on Vehicular Technology*, vol. 54, no. 3, pp. 763–770, May 2005.
- [10] M. Ehsani, Y. Gao, S. Gay, and A. Emadi, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*. Boca Raton, FL, USA: CRC Press, 2004.
- [11] T. J. E. Miller, *Switched Reluctance Motors and Their Control*. Oxford, U.K.: Oxford University Press, 1993.
- [12] R. Krishnan, "Switched reluctance motor drives: Modeling, simulation, analysis, design, and applications," *IEEE Transactions on Industrial Electronics*, vol. 35, no. 4, pp. 487–499, Nov. 1988.
- [13] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*, 3rd ed. Hoboken, NJ, USA: Wiley, 2003.
- [14] S. Morimoto, Y. Takeda, T. Hirasaka, and K. Taniguchi, "Expansion of operating limits for permanent magnet motor by current vector control considering inverter capacity," *IEEE Transactions on Industry Applications*, vol. 26, no. 5, pp. 866–871, Sep. 1990.
- [15] J. F. Gieras and M. Wing, *Permanent Magnet Motor Technology: Design and Applications*, 2nd ed. New York, NY, USA: Marcel Dekker, 2002.
- [16] K. Rajashekara, "Present status and future trends in electric vehicle propulsion technologies," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 1, pp. 3–10, Mar. 2013.
- [17] H. Abu-Rub, A. Iqbal, and J. Guzinski, *High Performance Control of AC Drives with MATLAB/Simulink Models*. Hoboken, NJ, USA: Wiley, 2012.
- [18] J. Dixon, L. Moran, J. Rodriguez, and R. Domke, "Reactive power compensation technologies: State-of-the-art review," *Proceedings of the IEEE*, vol. 93, no. 12, pp. 2144–2164, Dec. 2005.
- [19] S. Huang, J. Su, S. Dai, C. Tai, and T. Lee, "Enhancement of wireless power transmission with foreign-object detection considerations," in *Proc. IEEE 6th Global Conf. Consumer Electronics*, Nagoya, Japan, 2017, pp. 1–2.