Power Electronics Research and Applications Transactions
https://www.sciltp.com/journals/perat

Review

Wireless Motors—The Future of Untethered Drives

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How To Cite: Wang, H.; Liu, W.; Chau, A.M.H.; et al. Wireless Motors—The Future of Untethered Drives. *Power Electronics Research and Applications Transactions* **2026**.

Received: 22 June 2026
Revised: 24 July 2026
Accepted: 30 July 2026
Published: 14 August 2026

Abstract: For past centuries, electric motors have efficiently converted electrical energy into mechanical kinetic energy and have been widely deployed in industrial and domestic equipment. However, conventional motors rely on hardwired cable connections for power, which limits the motor's mobility. To further enhance the motor's flexibility and enable operation while moving, a variety of wirelessly powered motor topologies have been proposed and developed. This paper presents a comprehensive state-of-the-art review of existing wireless motor and drive systems, with a specific emphasis on integrated designs that merge wireless power transfer with load motors to eliminate secondary-side controllers. Five main types of wireless motors are discussed: wireless brushed motors, wireless AC motors, wireless switched reluctance motors, wireless stepper motors, and wireless ultrasonic motors. Their potential applications are explored, especially in environments that demand high flexibility, improved protection against electric shock, and suitability for fully sealed or isolated conditions. Also, the topologies of wireless energy transceivers for multi-phase wireless motors are introduced. Besides, multiple speed/position detection methods, namely, wireless resolver, wireless Hall, sensorless control, etc., are introduced, so that the primary controller can perform closed-loop control of the remote motor. At the end, this paper concludes by highlighting future research opportunities that can further advance these innovative power electronic drive systems.

Keywords: wireless power transfer; electric motor; primary control; secondary controllerless; maintenance-free operation

1. Introduction

Since Michael Faraday proposed Faraday's Law of Electromagnetic Induction, various types of electric motors have been developed and widely used in industry, domestic and deep-space/-sea exploration devices [1–3].

In mythology and folklore, heroes often struggle against ropes, nets, or bindings that sap their strength—and in literature, Gulliver in Lilliput is famously tied down by tethering strings. Based on the same token, conventional motors are bound to power cables, inevitably reducing their adaptability and flexibility [4–6]. For example, the power cables for in-wheel motors in electric vehicles (EVs) [7–9] could be worn and torn by the mechanical stress and vibration [10–12]. Also, implantable motor-driven artificial organs (e.g., artificial hearts) cannot be externally powered via cables [13], which usually rely on using batteries [14] that need to be replaced every 10 or 15 years through surgery [15].

Therefore, wireless motors—capable of contactless power supply—can deliver superior applicability and flexibility [16–18]. Notably, a well-packed and sealed wireless motor can operate in isolated or corrosive environments [19,20], including robotics [21–23], water pumps (Figure 1) [24], pipeline pigging [25], and medical applications [26,27].

To promote progress in this field, this paper introduces the most common wireless motors, including their topologies and position/speed detection methods (Figure 2). In Section 2, various wireless motors, including wireless brushed motors, wireless AC motors (including wireless brushless DC motor), wireless switched reluctance (SR) motors, wireless stepper motors, and wireless ultrasonic motors, are discussed, respectively. The topologies of transceivers are introduced in Section 3. In Section 4, the position/speed detection methods are introduced. In Section 5, the future trend for the development of wireless motors is briefly discussed. Finally, a conclusion is drawn in Section 6.

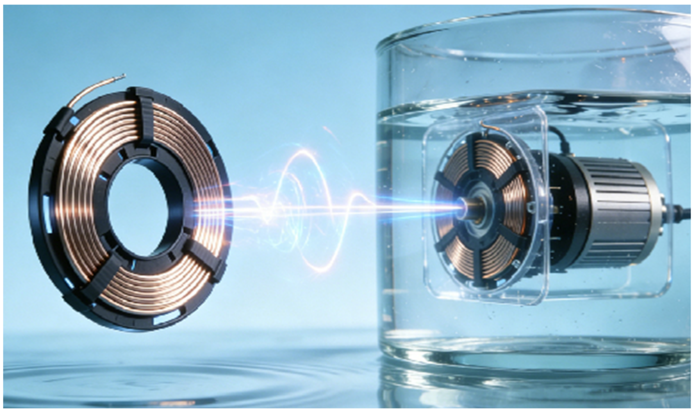


Figure 1. Wireless motor working in an isolated environment.

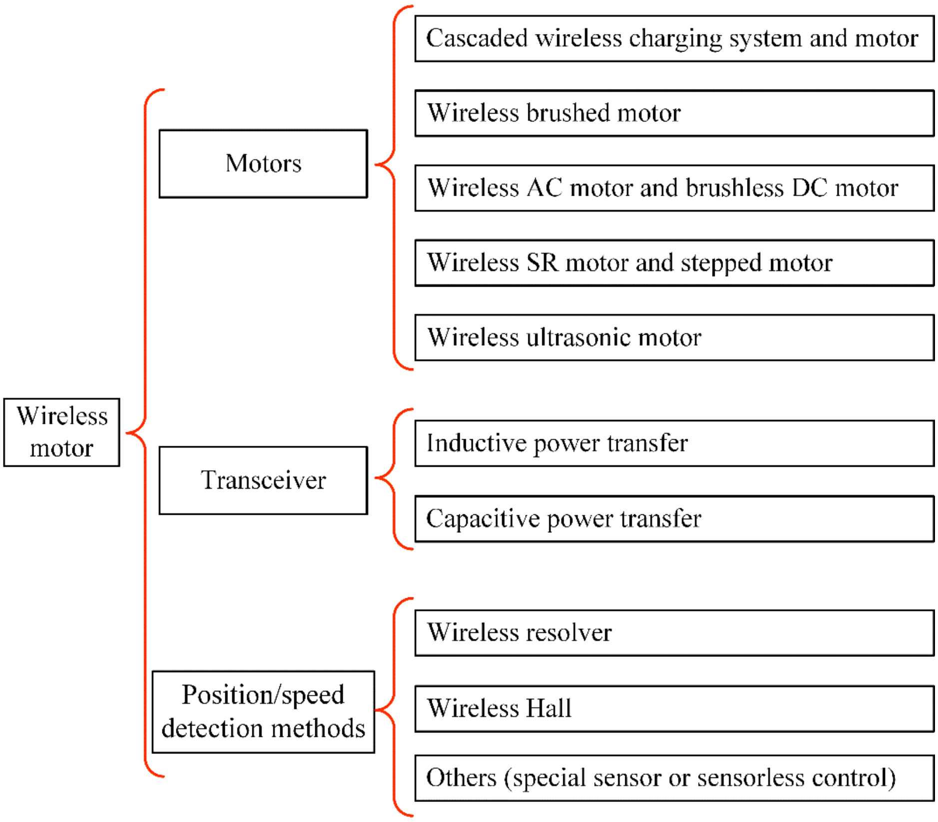


Figure 2. Current research achievements and classification of wireless motor technology.

2. Wireless Motors

The earliest wireless motor was a system that directly cascaded the wireless power transfer (WPT) system and the motor [28]. Even though it is compatible with all kinds of electric motors and control strategies [29–31], the secondary controller remains unstable and unreliable [32]. Therefore, this paper will focus on introducing the secondary-side controllerless motors, such as the wireless DC motor [33].

2.1. Wireless Brushed Motors

Same as the development sequence of traditional wired motors, the wireless brushed DC motor was first proposed. Because brushed motors use mechanical brushes for commutation [34], the system topology and control strategy are very simple [35,36].

For unidirectional operation, the secondary side can be very simple and does not require any active components. For bi-directional operation, however, the secondary circuit is much more complicated [37]. The main reason is that the secondary switches need a control module, even self-drive switches.

2.1.1. Wireless Unidirectional Brushed Motors

For the wireless permanent magnet (PM) DC motor, the secondary side consists only of a receiving circuit and a rectifier bridge, which are sufficient to control and drive the motor [38,39]. The motor terminal voltage V_M is [40–42]

$$V_M \approx V_{RI} = \mathrm{j}2\pi f \times M \times I_T \quad (1)$$

where V_{RI} is the input voltage of the secondary rectifier bridge, f is the WPT frequency, M is the mutual inductance, and I_T is the transmitter current.

Notably, the primary controller can control the load motor speed and power level via frequency modulation [43,44] or phase modulation. Therefore, WPT and the motor form a complete system rather than a cascading one, making it the first true wireless motor [33].

A wireless shunt-wound brushed motor is proposed in [21,45] (Figure 3). In theory, the system requires only one receiver and charges both the paralleled field and armature windings. However, this system utilizes two receivers with different resonant frequencies f_F and f_A, charging the field winding and armature winding separately. Thus, the transmitter side can regulate the armature current and field current independently by using a general microcontroller unit (MCU), making the control more flexible and enabling a wider range of speed regulation (such as the field weakening speed regulation) [46].

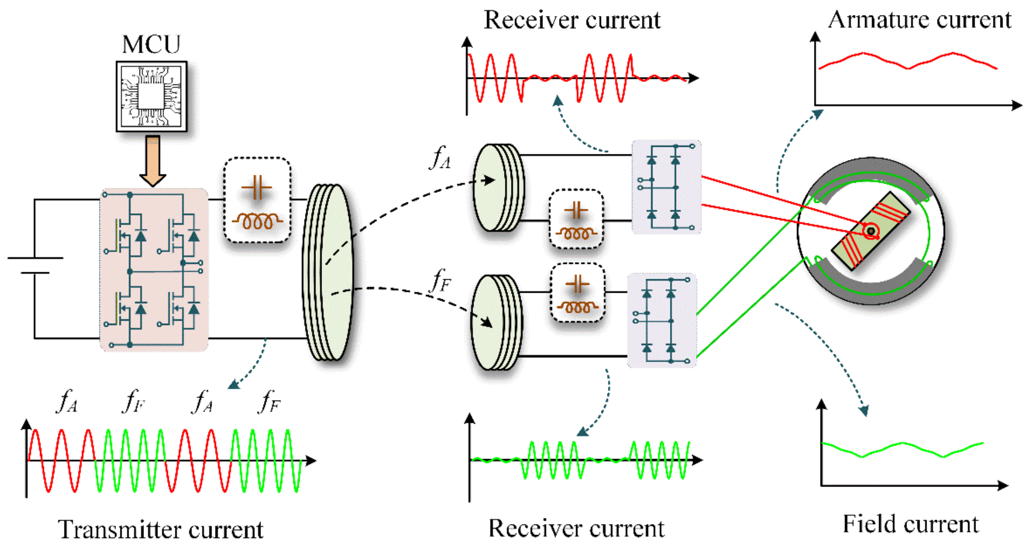


Figure 3. Topology of a wireless unidirectional shunt-wound brushed motor.

2.1.2. Wireless Bidirectional Brushed Motor

The first bidirectional wireless DC motor uses two receiving circuits to independently drive the motor clockwise and counterclockwise [47] (Figure 4a), and the control signals for the secondary switches (S_A and S_B) are derived from the secondary rectifier's input voltage. When the system operates at the frequency f_A, the top receiving circuit is resonant, so it can power the top rectifier bridge and turn on the switch S_A. Thus, the primary side can drive the motor in one direction. When the system operates at the frequency f_B, the bottom receiving circuit is resonant, so the bottom switch S_B is on and can drive the load motor in the other direction.

A wireless universal motor—a series-wound brushed motor that can operate on both AC and DC power—is proposed in [48] (Figure 4b). Unlike the former system, this one has only one receiver and two additional LC tuning circuits. The capacitor voltages (V_A and V_B) of these two LC tuning circuits can automatically control the secondary inverter.

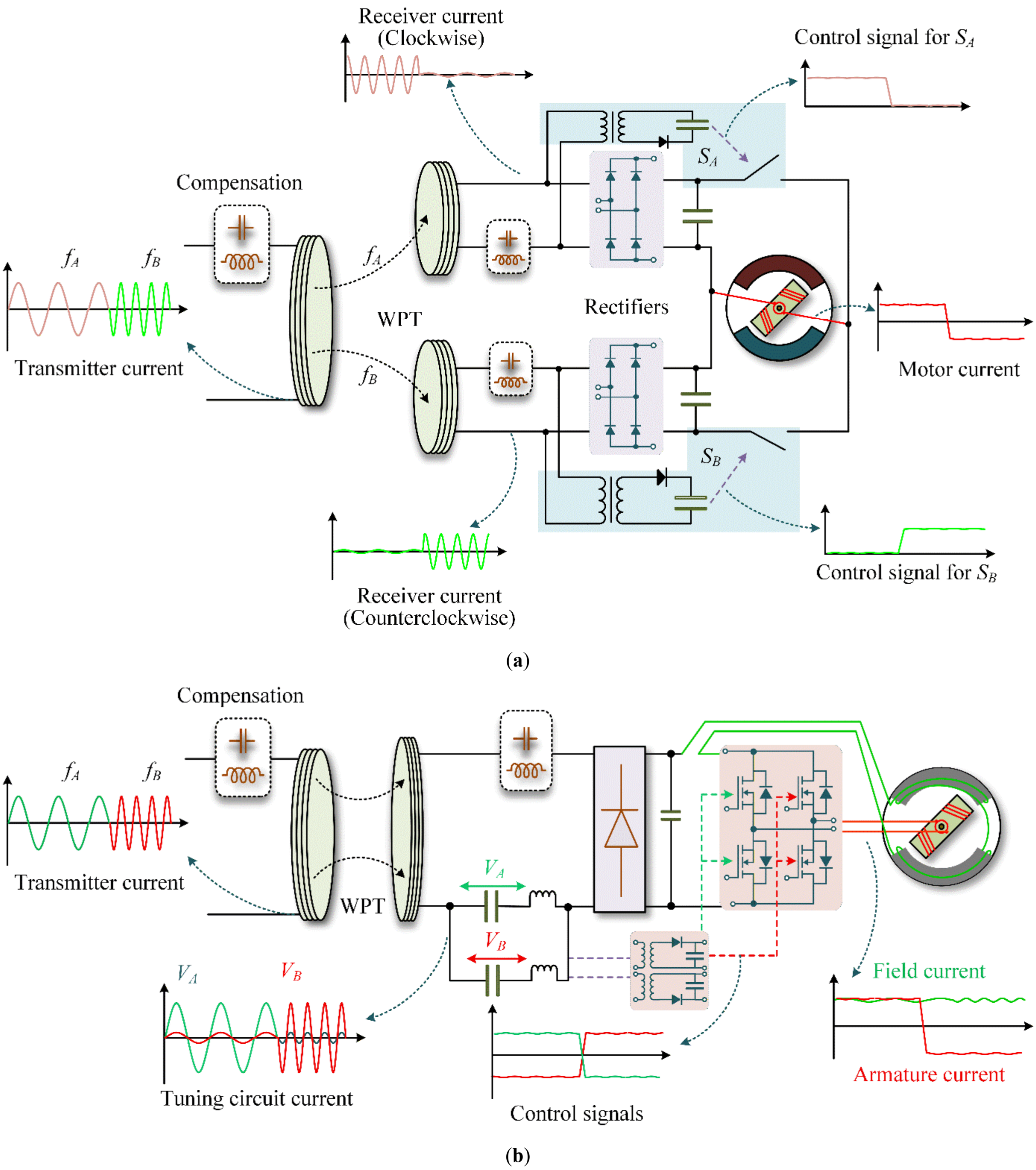


Figure 4. Topology of wireless bidirectional brushed motors. (**a**) With two receivers and two self-drive switches. (**b**) With a single receiver and four self-drive switches.

2.2. Wireless AC Motors and Brushless DC Motors

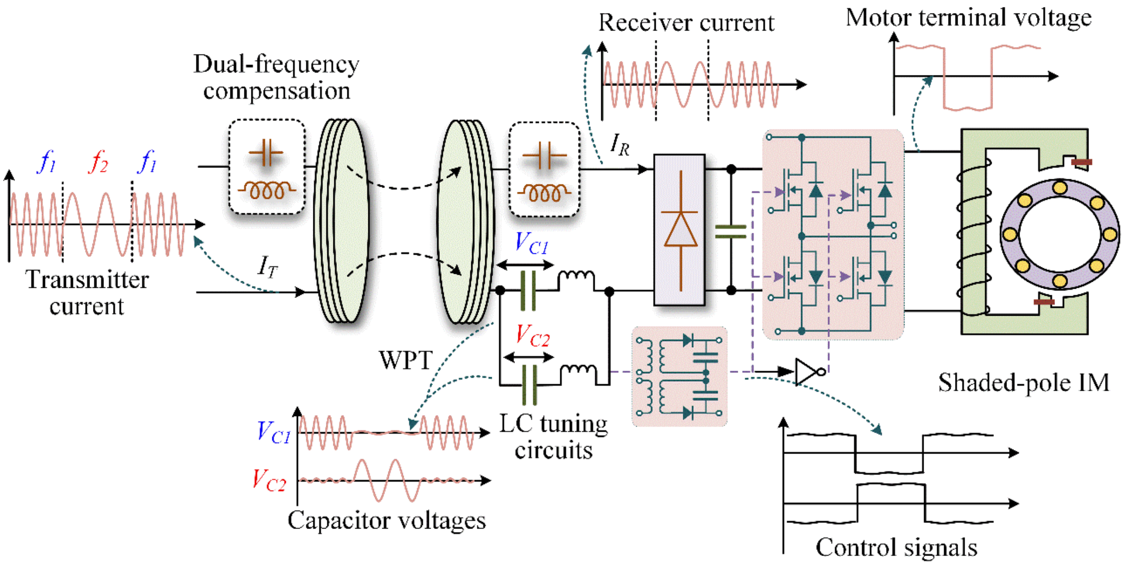
Even though wireless brushed motors have a simple structure and are easy to operate, the brushes and commutators are prone to wear and tear, requiring regular maintenance [49]. Thus, wireless AC motors have been developed to address these problems [50].

2.2.1. Wireless Single-Phase AC Motor

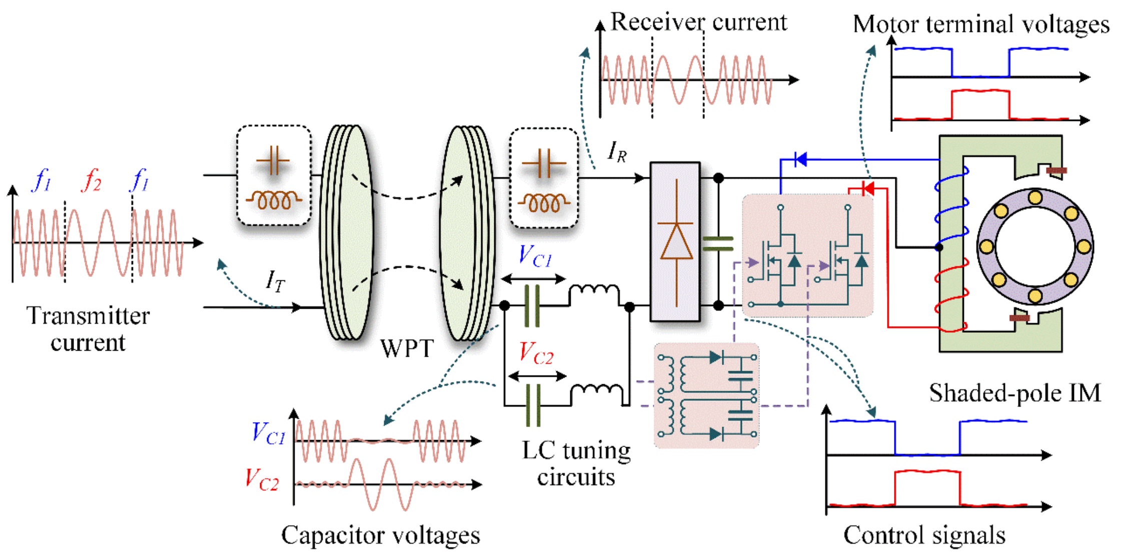
The first wireless shaded-pole induction motor (IM) is proposed in [51]. As shown in Figure 5a, it uses the same LC-tuning circuit and self-drive inverter as the wireless universal motor. Differently, the primary controller needs to regulate WPT frequency between f_1 and f_2 periodically to generate an alternating current for the load motor. Notably, the primary controller can regulate motor speed by regulating the frequency-hopping interval and transmission current proportionally.

To simplify the secondary side and eliminate the number of switches, a wireless shaded-pole IM with a half-bridge inverter is proposed in [52]. As shown in Figure 5b, by adding an additional stator winding, the system can generate an alternative magnetic field for the motor by periodically activating these two windings, or the system can use an additional three-winding transformer (Figure 5c) to drive existing single-winding motors [53].

To further simplify the system, a secondary inverter-less system is proposed in [54]. As shown in Figure 5d, the system drives the load motor's two windings independently. Therefore, the secondary side is extremely simple and can achieve sinusoidal motor currents. However, although two windings are not directly connected, they are magnetically coupled. Thus, they will induce voltage on each other, reducing the equivalent motor current and total efficiency.

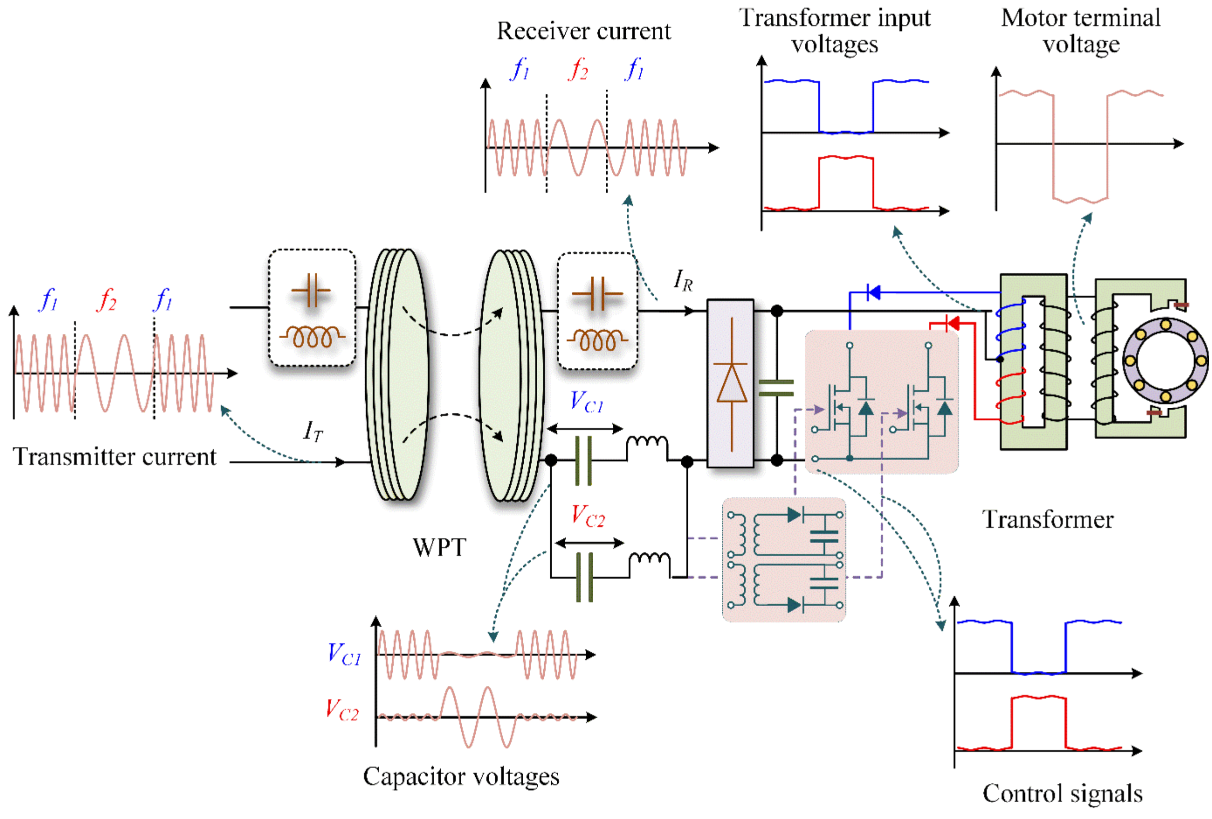


(a)

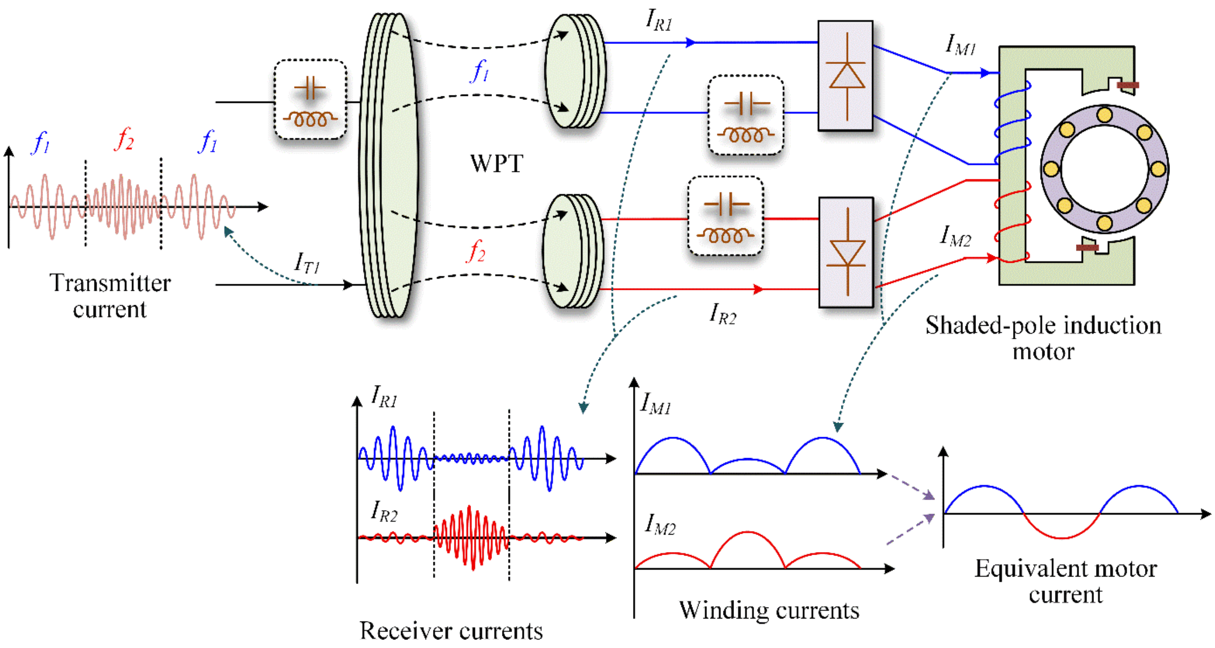


(b)

Figure 5. *Cont.*



(c)



(d)

Figure 5. Topology of wireless single-phase IM. (**a**) With a full-bridge self-drive inverter and a traditional IM. (**b**) With a half-bridge self-drive inverter and dual-winding IM. (**c**) With a half-bridge self-drive inverter and a traditional IM. (**d**) Without a secondary inverter and a dual-winding IM.

2.2.2. Wireless Three-Phase AC Motor

The first and fourth wireless single-phase AC motor systems (Figure 5a,d) have been further extended to three-phase systems. By adding more transceivers, the primary-side controller can control multiple phases, enabling additional advantages, such as bi-directional operation.

The first wireless three-phase brushless DC motor is proposed in [55]. The primary side can determine the motor's rotating direction by regulating the operating sequence of the three transceivers. Also, the system can select a 120° or 180° commutation strategy by selecting the number of transceivers that operate simultaneously.

A wireless secondary-converterless three-phase AC motor is proposed in [56]. By adopting dual-stator windings, the system can generate a rotating magnetic field without a secondary inverter. However, the drawbacks are the same as the single-phase AC motor [54], i.e., the two windings are coupled by a magnetic field. Thus, the idle winding induces a current and generates braking torque, thereby reducing system efficiency.

2.3. Wireless SR Motors and Stepper Motors

The wireless SR motor is very similar to the secondary-converterless AC motor, as the receiving circuit connects to the stator winding only through a simple rectifier bridge [57,58]. Differently, each stator phase only contains one winding, so the topology is much simpler (Figure 6) [59].

Similarly, a wireless stepper motor adopts a comparable structure [60]. By energizing the stator windings phase by phase, the system can generate a rotating magnetic field to pull the salient-pole rotor into rotation [61,62].

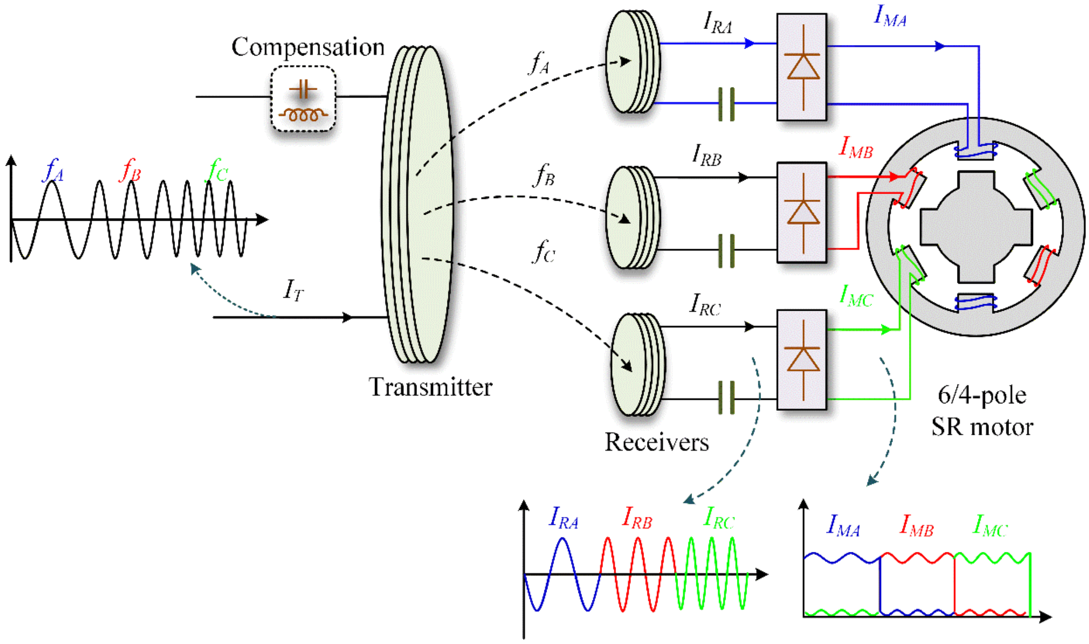


Figure 6. Topology of wireless SR motor.

2.4. Wireless Ultrasonic Motors: The Most Robust Wireless Motor

By now, the wireless ultrasonic motor is the only wireless motor that does not contain any brushes, switches, or diodes, which makes it the most robust motor (Figure 7) [63]. The key is the special mechanical structure of the ultrasonic motor, which requires it to be driven directly with a high-frequency current, so it can use the receiver's current [64].

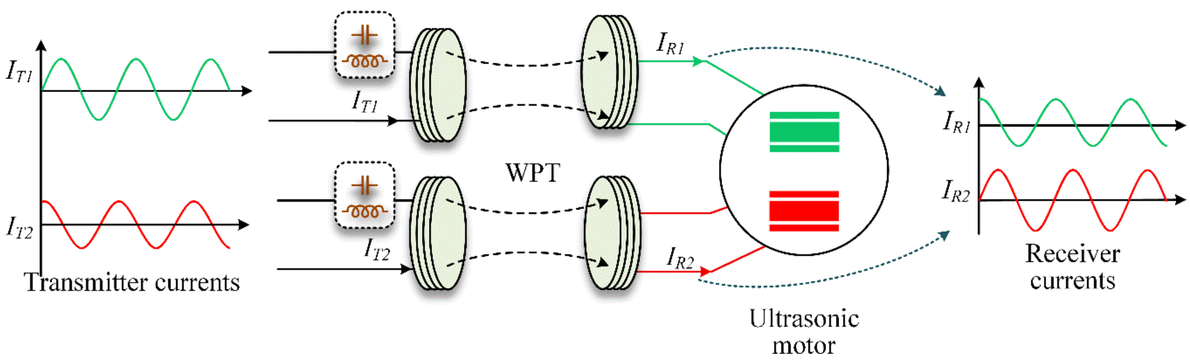


Figure 7. Topology of wireless ultrasonic motor.

3. Systems Topologies

3.1. Inductive Power Transfer

By now, most wireless motors use coils as transceivers because they are lighter and better suited for high-power transfer [65,66]. For single-phase WPT, only one pair of coils and a fixed compensating capacitor (single resonant frequency) are sufficient [67–69]. However, for multi-phase wireless motors, i.e., wireless SR motor, a multi-receiver system or a multi-frequency WPT system is preferred [70,71].

3.1.1. Multi-Receiver and Multi-Frequency System

The first multi-receiver systems used a single transmitter coil and three distributed receivers to charge a three-phase SR motor (Figure 8) [57,72]. To increase selectivity, the transmitter side uses switched-capacitor or high-order compensation to provide multi-frequency WPT [73], while each receiver can respond to only a single frequency.

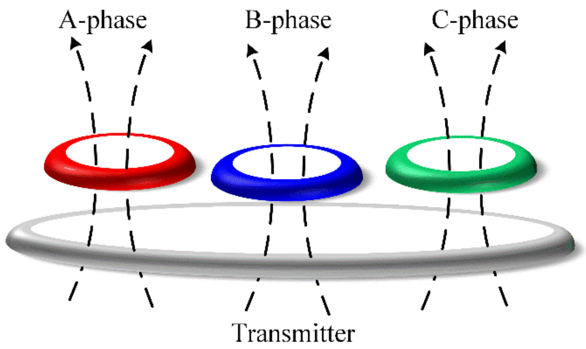


Figure 8. Topology of a multi-receiver and multi-frequency system.

3.1.2. Multi-Receiver and Single-Frequency System

To make the transceiver more compact, more wireless motors use orthogonal bipolar coils now [74,75]. By controlling the magnetic field direction, three pairs of coils can be placed together and share the frequency, while there is no crosstalk between phases (Figure 9). Thus, the primary side can selectively charge the receiver with a very small size.

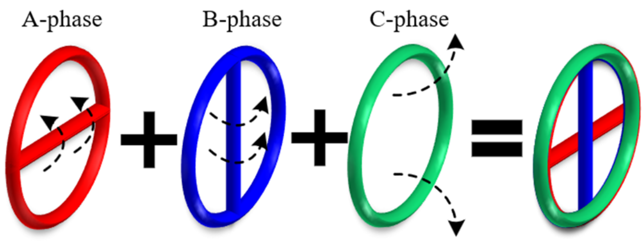


Figure 9. Topology of a multi-receiver and single-frequency system.

3.2. Capacitive Power Transfer

For low-power motors, capacitive power transfer is a good option as the transceivers can be ultra-thin [76]. As shown in Figure 10, each phase can transfer energy wirelessly with two pairs of transmitting and receiving electrodes [77].

Since capacitive power transfer transmits energy via an electric field, it causes negligible electromagnetic interference to the surrounding environment and incurs no iron loss or other magnetic losses [78,79]. This approach, however, requires extremely large electrode plates to achieve high-power energy transmission. Therefore, it is more suitable for small-scale motors such as implantable medical devices [26,80].

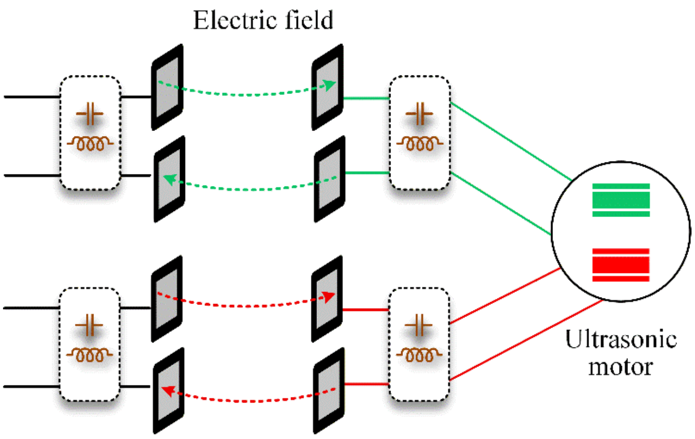


Figure 10. Topology of a capacitive power transfer system. Two phases (red and green) can transfer energy wirelessly and independently.

4. Position/Speed Detection Methods

Even though open-loop control can meet many application requirements, closed-loop control is essential, especially for medical or high-power applications [81–83]. Importantly, conventional wireless communication methods, such as Bluetooth or Zigbee, cannot meet the requirements of wireless motors [84,85]. Not only because of the milliseconds of communication delay [86,87], but also because the complicated power module will impair the stability of the motor side [88,89].

4.1. Wireless Resolver

The first position sensor for a wireless motor is the wireless resolver [90]. Since the resolver's rated frequency can reach 50 kHz [91–93], the wireless charging system can use a small current transformer to isolate power and charge the resolver directly (Figure 11).

With two small signal-transfer coils, the resolver can feed the motor position signals back to the MCU in time.

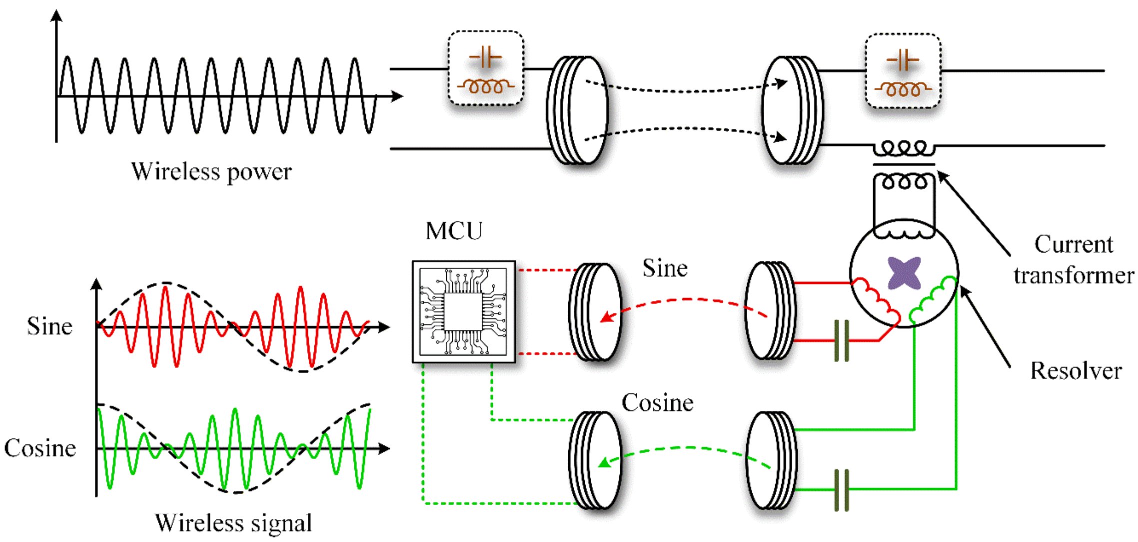


Figure 11. Topology of wireless resolver.

4.2. Wireless Hall

Wireless Hall sensors have also been proposed. However, due to the Hall sensors' special power level requirements, they must be powered via additional wireless power coils [94].

In Figure 12a, a system uses three wireless signal coils to transfer three Hall signals back to the primary controller, with each coil controlled by a separate Hall sensor [95].

In Figure 12b, the system used three resistors (R_A, R_B, and R_C) at the Hall side to change the system load when charging Halls [96]. As the total resistance of the secondary side, R_2, is determined by the parallel connection of these resistors ($R_A << R_B << R_C$), and the transmitter current I_T is proportional to the secondary resistance R_2 [97,98], the Hall signal can affect the transmitter current at the primary side directly.

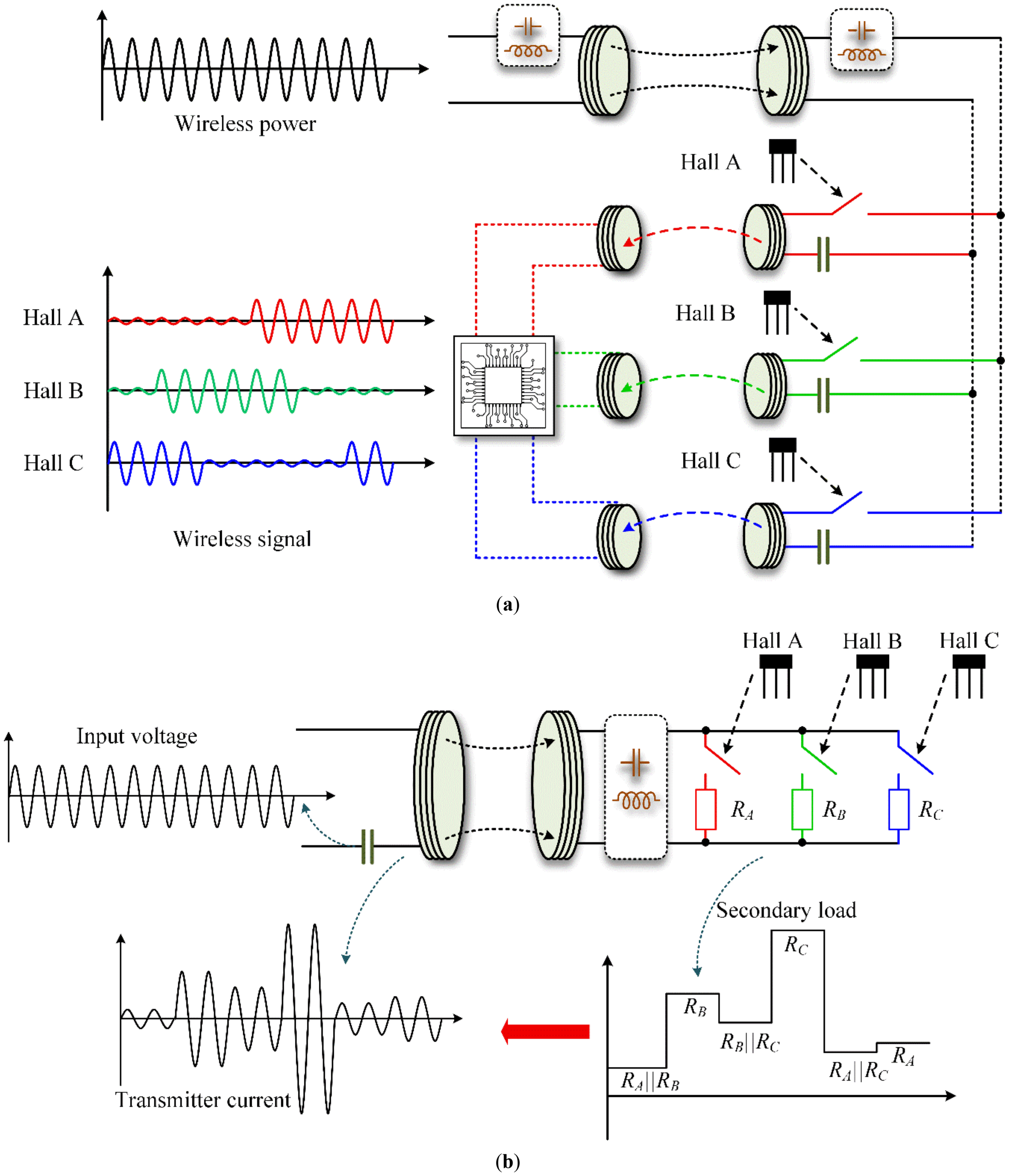


Figure 12. Topology of wireless Hall. (**a**) With one power transfer coil and three feedback signal transfer coils. (**b**) With one power transfer coil.

4.3. Others

Some wireless motors can use specialized position or speed detection methods. The key is using the special mechanical structure of the load motors and the coupling effect between the primary and secondary sides.

For wireless brushed motors, the primary controller can detect the ripples in the transmitter current to calculate motor speed, as these ripples are caused by carbon brush commutation [48]. Similarly, the wireless three-phase AC motor system can extract motor position information from the high-frequency current signal on the primary side [99].

For the wireless ultrasonic motor, a highly integrated magnetic coupler can transfer speed information to the primary side, and the high-frequency speed information is generated by the motor itself [63].

5. Discussions

Table 1 compares the main wireless motor topologies discussed in this paper, including the motor type, main advantages, limitations, sensing/control requirements, and typical application areas.

Among all secondary controllerless wireless motors, the most robust wireless motor is the wireless ultrasonic motor, followed by the wireless SR motor, wireless stepper motor, wireless AC induction motor, wireless brushless DC motor, and wireless brushed DC motor. As the first one is a secondary semiconductorless, while the others at least need a secondary rectifier bridge. However, for high-power applications, the best choice is the wireless SR motor with wireless resolver, as it offers a simple mechanical structure, easy control, high power density, and no demagnetization risk.

In the future, more sensorless control strategies are needed in this field [100], as resolvers are expensive and wireless Hall sensors require additional power supply coils. Even though some sensorless control strategies have been proposed, they are only suitable for specific motors [101]. Thanks to the development of artificial intelligence (AI), software-based real-time detection is easier [102–104]. Also, this combination will help the controller tune to compensate for parameter variations [105], ensuring stable and efficient operation without physical sensors in future [106]. Moreover, wireless motor can incorporate with dynamic wireless charging for EVs [107] and may even achieve bidirectional energy transfer [108–110].

Table 1. Comparison of wireless motors.

Types	Advantages and Limitations	Control Strategies	Typical Applications
Wireless brushed motors	✓ Secondary side is transistor-less (for unidirectional operation) × Secondary side needs transistors (for bi-directional operation) × Carbon brush is not robust	➢ Speed control: Regulate transmitter current amplitude ➢ Direction control: Regulate frequency	➢ Submersible sewage pump ➢ Logistics vehicles
Wireless AC Motors and brushless DC Motors	✓ Secondary side is brushless ✓ Secondary side can be transistor-less (low power operation) × Secondary side needs transistors (high power operation)	➢ Speed control: Regulate transmitter current amplitude ➢ Direction control: Regulate frequency order (three-phase motor)	➢ Cleaning pig ➢ Capsule robots
Wireless SR motor and stepped motor	✓ Secondary side is transistor-less × High torque ripple	➢ Speed control: Regulate transmitter current amplitude ➢ Direction control: Regulate frequency order or phase order	➢ Robotics ➢ In-wheel motor
Wireless ultrasonic motor	✓ Secondary side is semiconductor-less × Low efficiency of ultrasonic motor	➢ Direction control: Regulate phase order	➢ Most situations, including implantable medical devices

6. Conclusions

This paper has explored the concepts, advancements, and emerging directions of a new class of electronic driving systems, namely wireless motors. Special attention has been given to the system architectures, operational mechanisms, and control methods for wireless DC motors, wireless shaded-pole induction motors, wireless SR motors, etc. Several speed/position detection methods for achieving closed-loop control in these systems have also been explored. Both the advantages and limitations of wireless motors have been outlined. Overall, wireless motors show significant promise for use in industrial, transportation, and medical settings, particularly where equipment must operate in isolated or hard-to-reach locations. Future research directions include the development of wireless sensorless control strategies and AI-driven real-time compensation tuning methods.

7. Biographies of the Authors

Hui Wang (Member, IEEE) received the B.Eng. degree in electrical and electronic engineering from Shandong University of Science and Technology, Qingdao, China, in 2014, and the M.Eng. degree in electrical and electronic engineering from Tianjin University, Tianjin, China, in 2017. In 2022, he received the Ph.D. degree in electrical and electronic engineering from the University of Hong Kong (HKU), Pokfulam, Hong Kong, China. He is currently a Research Assistant Professor at the Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University. Before that, he worked as a Postdoctoral Associate with the Brain Stimulation Engineering Lab, Duke University, the Department of Electrical and Computer Engineering, Rhineland-Palatinate Technical University, and the Department of Electrical and Electronic Engineering, HKU. His research interests include electric machines, bioelectronics, biomedical electronics, electric vehicles, and wireless power transfer technologies.

Wei Liu (Senior Member, IEEE) received the B.Eng. and M.Eng. degrees in electrical engineering from China University of Petroleum, Qingdao, China, and a Ph.D. degree in electrical and electronic engineering from The University of Hong Kong (HKU), Hong Kong, China, in 2014, 2017, and 2021, respectively. He is currently an Assistant Professor at the Research Centre for Electric Vehicles and Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University (PolyU). He has also been an Honorary Assistant Professor at the Department of Electrical and Electronic Engineering, HKU, since 2023. Dr. Liu served as a Postdoctoral Fellow and was then promoted to a Research Assistant Professor from 2021 to 2023. He also worked as a Visiting Researcher with Nanyang Technological University, Singapore (NTU), in 2019. His research interests include electric vehicle technologies, wireless power transfer, power electronics, bioelectronics, and semiconductor devices. Dr. Liu was the recipient of two Gold Medals with Congratulations of the Jury in the International Exhibition of Inventions Geneva, the Second Place Prize Paper Award of IEEE Journal of Emerging and Selected Topics in Power Electronics (JESTPE), the Power Engineering Prize from HKU, the Excellent Paper Award, and the Best Presentation Award from international conferences in the area of Electric Vehicles and Transportation Electrification. He is also a Guest Associate Editor of IEEE JESTPE, Associate Editor of international journals, and Session Chair of international conferences.

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Author Contributions

H.W.: Writing—original draft. W.L.: Writing—review & editing. A.M.H.C.: Writing—review & editing. K.T.C.: Conceptualization, Funding acquisition, Supervision. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported in part by the Hong Kong Research Grants Council, Hong Kong Special Administrative Region, China (Grant No. 15204426 and Grant No. 17206222), and in part by The Hong Kong Polytechnic University (Grant No. P0046563 and Grant No. P0054038).

Data Availability Statement

Not applicable for review paper.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used AI tool Seedream to generate Figure 1. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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