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Direct wireless power conversion systems and their applications

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1. Introduction

In recent years, wireless power transfer (WPT) has been becoming popular due to its electrocution-free, better convenience and higher flexibility.[1-3] Based on these definite advantages, the WPT technology has been widely developed for many applications such as biomedical implants [4, 5] and electric drones.[6, 7] In particular, the wireless charging of electric vehicles has been actively investigated, with emphasis on its dynamic performance [8-10] and security consideration.[11-13]

Almost all WPT applications are essentially based on electrochemical power conversion. Namely, after retrieving the wireless power from the transmitter, the receiver charges the batteries by converting the electrical power into chemical processes; consequently, these batteries will be discharged to reproduce electrical power from chemical processes for various applications, such as powering other electric devices, electromechanical motion, electric lighting and electric heating. This electrochemical power conversion heavily relies on using batteries for energy storage, which is inefficient, bulky size, heavy weight, expensive and of limited cycle life.[14, 15]

In order to get rid of the batteries for WPT applications, the concept of direct wireless power conversion (DWPC) becomes highly desirable. On top of battery-free, the electronic controller should also be avoided at the receiver side so that the device can be operated remotely in isolated environment and is totally maintenance-free. Thus, the direct control can be fully handled at the transmitter side. Very recently, this DWPC concept has been actively developed, with emphasis on wireless electromechanical power conversion, wireless electric lighting and wireless electric heating. The purpose of this paper is to give an overview of key DWPC systems, namely the wireless motors, wireless lamps and wireless heaters. Their operation principles and emerging applications will also be discussed.

In Section 2, recently developed wireless motors and their applications will be discussed. Then, in Section 3, wireless lamps and their control techniques will be discussed. Then, in Section 4, wireless heaters with emphasis on their advantages over existing induction heaters will be elaborated. Finally, in Section 5, a conclusion on these DWPC technologies will be drawn.

2. Wireless motors

Among so many WPT applications, the WPT for motors has been little researched. Over the years, it was mainly applied to wirelessly transfer power to rotatable field windings in generators, hence eliminating the mechanical slip-rings and carbon brushes. Recently, a wireless in-wheel motor using magnetic resonant coupling (MRC) was developed for electric vehicles, aiming to remove the cables for powering the motor and hence the associated risk of disconnection.[16] However, this is actually a combination of the WPT and the motor, which suffers from using an additional controller at the motor side. Most importantly, this kind of pseudo-wireless motor cannot be utilized to work at isolated or inaccessible environment because the controller has a much shorter lifespan than the motor.

The development of wireless motors without using bat-

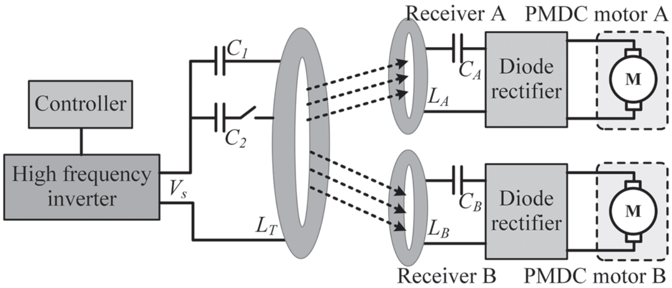

Figure 1: Wireless PM DC motor system

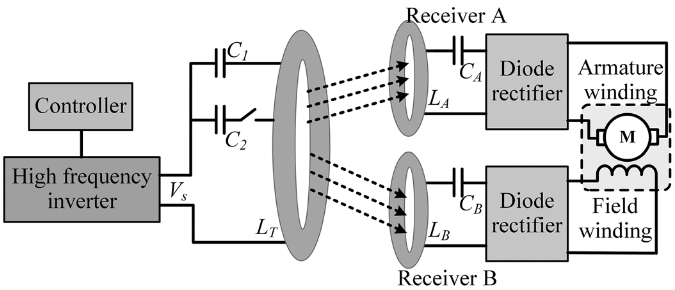

Figure 2: Wireless separately excited DC motor

teries or controllers at the motor side was kicked off in 2017. As shown in Figure 1, a wireless permanent-magnet (PM) DC motor system was developed in which multiple PM DC motors can be wirelessly and individually controlled for robotic applications.(17) Differing from using multiple transmitters and receivers (18), the transmitter can be purposely tuned to the specified resonant frequency which matches with the specified receiver coil, hence driving the specified motor selectively. Meanwhile, burst firing control (BFC) is used to regulate the operating speed of the motor working at the resonant frequency, hence retaining the maximum transfer efficiency. Then, a wireless separately excited DC motor was developed, as depicted in Figure 2, in which the transmitter can transfer power to two receiver coils simultaneously while their power transfers can be independently controlled by using time-division multiplexing.(19) Thus, the armature and field currents can be properly adjusted by using BFC to achieve the desired constant-torque and constant-power operations.

By incorporating the self-drive circuitry to switch the rotation direction based on the operating frequency of the transmitter, the wireless PM DC motor was further extended to derive the wireless servo motor as shown in Figure 3, hence offering bidirectional servo motion.(20) The key is to adopt the inductor-capacitor-inductor (LCL) compensation network at the transmitter so that the switched-capacitor array for the multiple-frequency WPT can be eliminated and the two receiver coils can offer power equalization for bidirectional servo motion. Prominently, there is no controller at the servo motor side, and the motor control can be effectively conducted at the transmitter side by using phase-shift control.

A promising application of wireless DC motors was proposed for underground in-pipe pumping drainage system as depicted in Figure 4, where an energy-carrying electric vehicle parks above the underground in-pipe pump motor, which

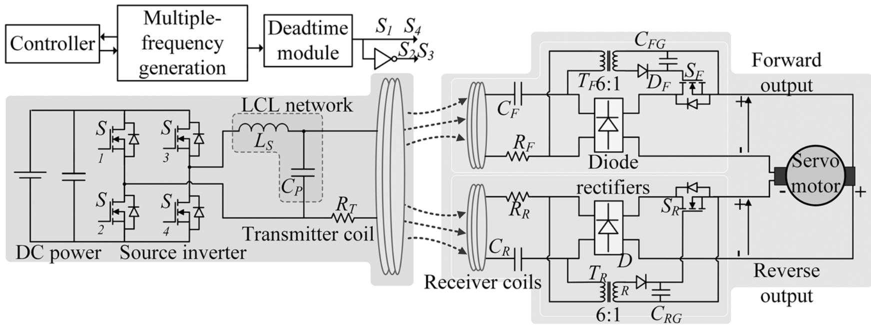

Figure 3: Wireless servo motor

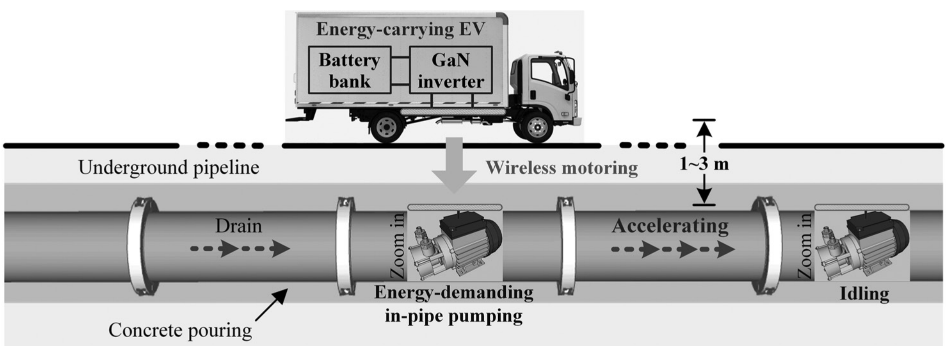

Figure 4: Underground in-pipe pumping drainage system using wireless motoring

wirelessly feeds the motor to directly control the water flow rate inside the pipe.[21] It can offer an emergency response to prevent severe water flooding.

In order to further improve the reliability and robustness for operation in isolated environment, the wireless switched reluctance motor (SRM) was proposed as shown in Figure 5.[22] Based on the same principle of wireless DC motors, three receiver coils are separately tuned at three different resonant frequencies and then directly fed into phase windings via diode rectifiers. Thus, each phase can be sequentially excited by each receiver coil at a particular resonant frequency. In order to get rid of the switched-capacitor array at the transmitter side, the inductor-capacitor-capacitor (LCC) compensation network was also developed to directly energize the three phase windings using different resonant frequencies.[23] Since the use of rotor position sensor and Bluetooth low energy (BLE) feedback inevitably degrades the system reliability, active research is being conducted to develop a position sensorless technique for this wireless SRM.

Since the shaded-pole induction motor (SPIM) is one of the most popular AC motors for domestic appliances, the wireless SPIM was proposed[24], which is actually the first wireless AC motor. As shown in Figure 6, there is no controller at the SPIM side, and the corresponding power switches are all self-driven. Meanwhile, the control process is fully conducted at the transmitter side, and there is no need to specially design the motor as all existing SPIMs can readily be used. By employing LCL compensation at the transmitter and switched LC compensation at the receiver, it can provide variable-voltage variable-frequency control for wide-range speed control of the SPIM.

3. Wireless lighting

High-intensity discharge (HID) lamps have been widely adopted for various lighting purposes because of their good color rendering index, high luminous efficacy and long service life.[25] For instance, indoor lighting prefers fluorescent lamps and metal-halide (MH) lamps, whereas outdoor lighting prefers high-pressure sodium (HPS) lamps and low-pressure sodium (LPS) lamps. In recent years, the light-emitting diode (LED) lamps are becoming popular because of their exceptionally long service life.

All types of HID lamps need a ballast to provide high igni-

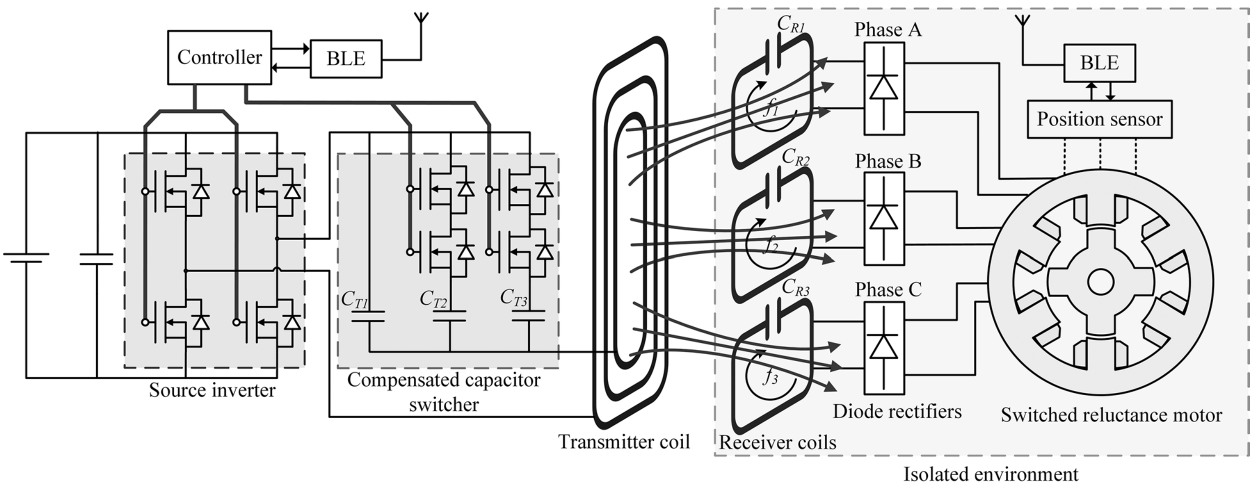

Figure 5: Wireless switched reluctance motor

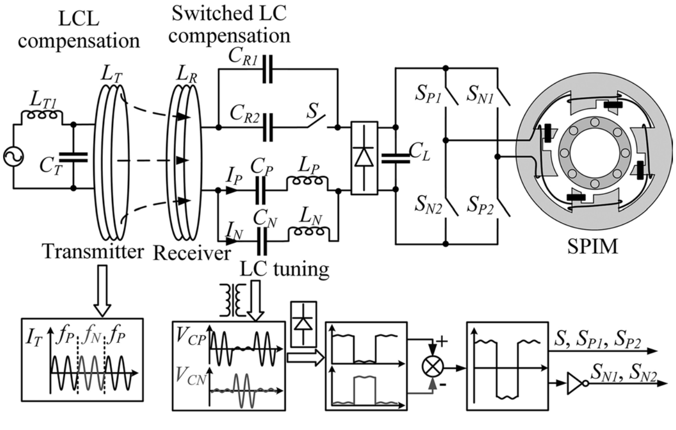

Figure 6: Wireless shaded-pole induction motor

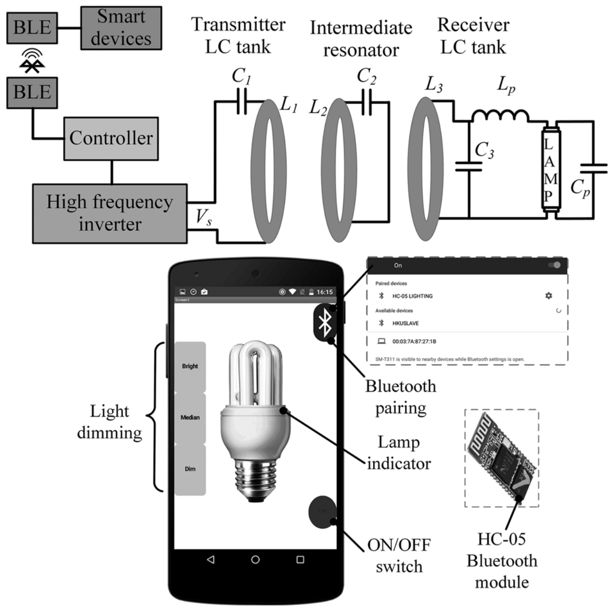

Figure 7: Wireless fluorescent lamp

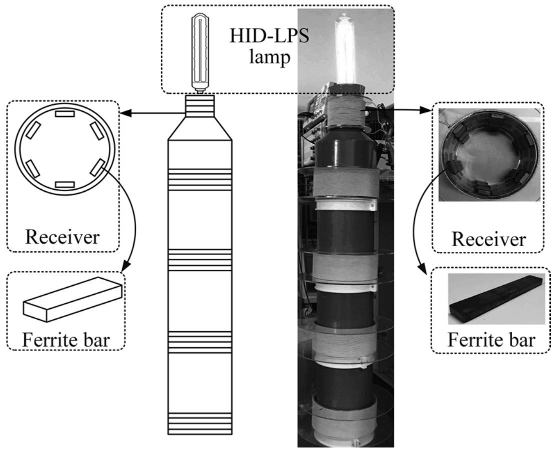

Figure 8: Wireless low-pressure sodium lamp

tion voltage and relatively low voltage for steady-state operation. This ballast, either magnetic or electronic, is bulky or expensive. Most importantly, it is risky to handle such high voltage in an outdoor environment. Thus, wireless lighting, which is free from electrocution under all-weather conditions, is highly desirable. The first wireless dimmable lighting was developed for a fluorescent lamp.[26] As shown in Figure 7, this wireless fluorescent lamp utilizes MRC to achieve WPT while igniting the fluorescent lamp without using any magnetic or electronic ballast. Also, BFC is utilized to achieve efficient light dimming. In order to achieve the fully wireless feature, remote lighting control via BLE can be realized by a smart phone. Then, the wireless lighting was extended to the MH lamp.[27] In order to offer high ignition voltage and low current stress, a high-order compensation network, namely the LCC-LC, is designed for this wireless MH lamp. Since the LPS lamp possesses the highest luminous efficacy among all types of lamps, the wireless LPS lamp was developed for street lighting.[28] As shown in Figure 8, this wireless lamp is ignited solely by the resonator without using any ignitor, ballast, or additional LC tank. Then, the series-capacitor-inductor-capacitor (S-CLC) compensation network and pulse-frequency-modulation control are developed for the wireless LPS lamp so as to concurrently achieve effective dimming control, reduced operating frequency and zero-voltage switching.[29]

Compared with wireless HID lamps, wireless LED lamps are more actively developed.[30] As shown in Figure 9, a wireless LED lamp is designed by integrating a secondary T-type LCL compensation network into sealed antiparallel LEDs [31], which takes the definite merits of safety, maintenance-free and convenience for manufacturing. In contrast to phase shift control, a WPT-inherent variable-power variable-frequency (VPVF) control is developed to effectively widen the dimming range and improve the voltage deviation tolerance. Also, the switching frequency and switching losses can be suppressed, hence improving the efficiency of this wireless LED lamp.

4. Wireless heating

Due to inherent safety and convenience, induction heat-

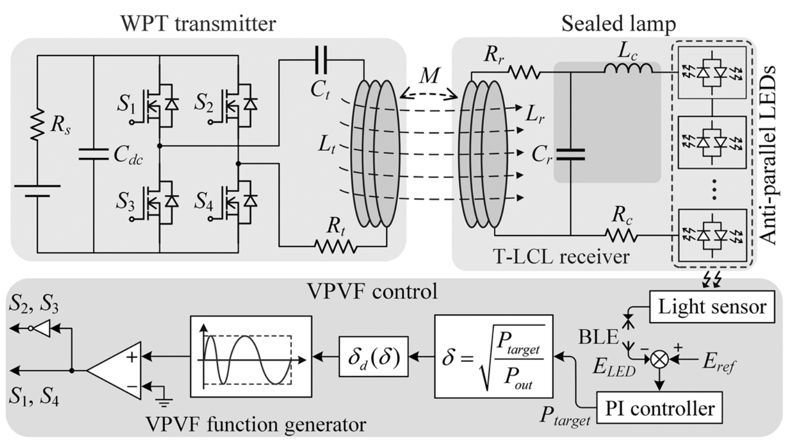

Figure 9: Wireless LED lamp

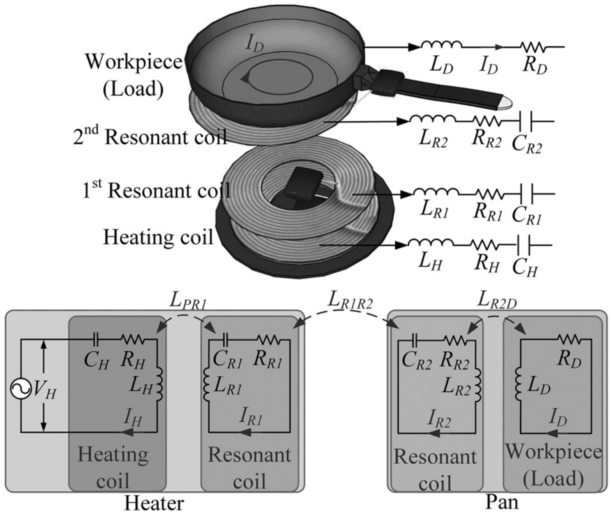

Figure 10: Wireless flexible heater

ing has been widely developed in the past few decades.(32) However, the existing induction heating is inevitably limited to heat the flat-bottom ferromagnetic conductive utensils through the magnetic inductive coupling (MIC). By using the MRC mechanism, wireless heating is being actively developed. As shown in Figure 10, the wireless flexible heater adopts one resonant coil located on the cooktop and one resonant coil located beneath the utensil, which can significantly strengthen the magnetic coupling effect.(33) It is particularly attractive to handle the requirements of flexibly varying vertical displacement and horizontal misalignment for various cooking styles. Moreover, the MRC mechanism was applied to a wireless heater to effectuate the homogenous heating effect.(34)

Existing induction heating can effectively heat a ferromagnetic conductive pan (such as an iron pan), but is incapable of heating a non-ferromagnetic conductive pan (such as an aluminum pan) as it will cause high current stress at the power source. Recently, the wireless all-metal heater was developed, which can effectively heat utensils made of various metallic materials.(35) Consequently, the concept of wireless all-metal heating was extended to wireless all-utensil heating, where the non-ferromagnetic non-conductive pan (such as a ceramic pan) can be heated by a stainless-steel disc put inside the utensil.(36) As shown in Figure 11, this wireless heater consists of double-layer concentric coils with their compensated capacitors connected in series. Differing from using a higher frequency to separately heat the non-ferromagnetic pan, it employs a single frequency to operate at the high-voltage

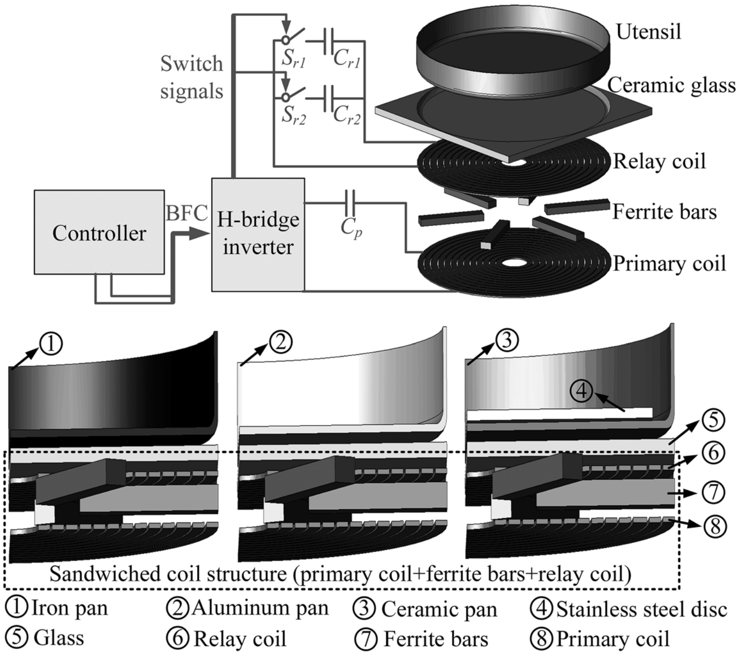

Figure 11: Wireless all-utensil heater

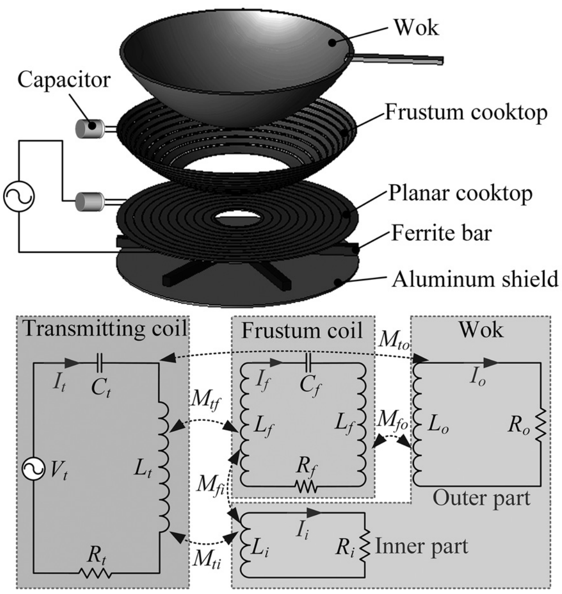

Figure 12: Wireless all-in-one heater

low-current and low-voltage high-current modes to effectively heat the ferromagnetic and non-ferromagnetic pans, respectively. Moreover, the required high current can be shifted from the primary coil to the resonant coil, hence significantly reducing the current stress at the power source.

Another limitation of existing induction heating is the incapability of heating both the flat-bottom utensil (such as a pan) and curve-bottom utensil (such as a wok) based on the planar cooktop. Recently, the wireless all-in-one heater was developed.[37] As shown in Figure 12, it employs a detachable frustum cooktop, which is actually a frustum coil coated with heat-resistant resin, so that both MIC and MRC are utilized to achieve excellent heating performance of the wok based on the planar cooktop. Focusing on heating the wok, which is much more demanding than heating the pan, the frustum coil serves to provide the MRC mechanism to boost the magnetic coupling of the outer part of the wok with a large air gap, while the inner part of the wok with a small air gap is heated by the MIC mechanism.

5. Conclusion

In this paper, a new theme of DWPC systems, which includes wireless motoring, wireless lighting and wireless heating, has been presented. Firstly, the operating principles of major wireless motors, including the wireless PM DC motor, wireless separately excited DC motor, wireless servo motor, wireless SRM and wireless SPIM, and their promising applications are elaborated. Secondly, the operating principles of major wireless lamps, including the wireless fluorescent, wireless MH lamp and wireless LPS lamp, and their potential applications are revealed. Thirdly, the operating principles of major wireless heaters, including the wireless flexible heater, wireless all-metal heater, wireless all-utensil heater and wireless all-in-one heater, and their major applications are discussed. It is anticipated that these DWPC systems will play an important role in both domestic and industrial applications.

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