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Review

Smart Wireless Power Transfer — Opportunities and Challenges

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Abstract: Popularization of wireless power transfer (WPT) has promoted the multi-disciplinary explorations and integration. It gradually incubates numerous attractive solutions for industrial, domestic and medical scenarios. Therefore, a series of smart WPT emerges, and these state-of-the-arts will bring a great impact on the modern technology and human society. This review investigates and discusses the opportunities and challenges of the smart WPT, especially in the areas of wireless energy modulation, conversion and intellectualization. The key is to reveal the methodologies, approaches and foresights for the emerging technologies of the smart WPT. As one of the most promising development trends, the smart WPT will embrace the information-energy internet and construct the wireless energy router and wireless energy internet that support the wireless energy trading for peers, communities and energy internets.

Highlights

- Methodologies, approaches and features of the smart WPT are discussed.
- Wireless energy modulation, conversion and intellectualization are presented.
- Foresights and development trends of future smart WPT are envisioned.
- Wireless energy router and internet will support wireless energy trading as well as wireless data and energy sharing in smart cities.

Keywords: Wireless energy modulation; Wireless energy conversion; Wireless energy intellectualization; Wireless energy internet; Wireless energy router; Wireless energy trading.

Nomenclature

WPT	wireless power transfer	PM	permanent magnet
IPT	inductive power transfer	PMSM	permanent magnet synchronous motor
CPT	capacitive power transfer	CC	constant current
EV	electric vehicle	CV	constant voltage
DC	direct current	MCC	maximum current charging
AC	alternating current	MHC	most healthy charging
PWM	pulse width modulation	STC	shortest time charging
PDM	pulse density modulation	MF	multi-frequency
PFM	pulse frequency modulation	RF	radio frequency
PAM	pulse amplitude modulation	MIMO	multiple-input multiple-output
PPM	pulse position modulation	WPIT	wireless power and information transfer
HFP	hybrid frequency pacing	WIT	wireless information transfer
ZVS	zero voltage switching	WPDT	wireless power and drive transfer
MEPT	maximum efficiency point tracking	WDT	wireless drive transfer
PFC	power factor correction	FDE	frequency-and-duration encryption
BMS	battery management system	LIB	lithium-ion battery
THD	total harmonic distortion	AI	artificial intelligence
HID	high-intensity discharge	SiC	silicon carbide
LED	light-emitting diode	GaN	gallium nitride
IM	induction motor	FET	field-effect transistor
SRM	switched reluctance motor	HV	high voltage

MV	medium voltage	P2C	peer-to-community
LV	low voltage	C2I	community-to-internet
EI	energy internet	V2V	vehicle-to-vehicle
WER	wireless energy router	V2H	vehicle-to-home
IoT	Internet of Things	V2C	vehicle-to-community
P2P	peer-to-peer	V2G	vehicle-to-grid

1. Introduction

Over one century ago, Nikola Tesla invented and patented the cordless electric energy transfer [1, 2]. Recently, electromagnetic resonant coupling and new physical concepts have greatly advanced the development of wireless power transfer (WPT) technologies [3-5]. As one of the most attractive research hotspots, plenty of industries and governments gradually recognize the competitive advantages of WPT technologies, such as larger power capacity, higher energy efficiency, better flexibility and strong security [6-8]. Besides, this contactless energy transfer brings the superiority of waterproof, sparkproof and shockproof [9]. Typically, wireless charging will effectively alleviate the over-independence of rechargeable batteries for millions of electric vehicles (EVs) [10, 11] and billions of portable electronics [12, 13]. On top of wireless charging, the emerging WPT technologies play a significant role in promoting the interdisciplinary collaborations and incubating some brand-new concepts or schemes [14-16]. Promisingly, the WPT will make continuous contributions in the areas of traffic, energy, information and medicine [17-19].

The WPT can be classified into the far-field WPT and the near-field WPT [20]. The far-field WPT usually uses the radio-frequency (RF) signal (covering microwave), optical carrier (such as laser) or acoustic/ultrasonic wave. Because wireless energy emitted from the antenna(s) should experience a long-range propagation [21], the far-field WPT suffers from low transmission efficiency, low power capacity and serious safety concerns due to electromagnetic field exposure [22-24]. The near-field WPT can be further classified into the short-range WPT and medium-range WPT. It adopts electromagnetic fields as the energy carrier and achieves the high-efficiency and non-radiative features [4, 25]. The short-range WPT including the purely inductive and capacitive WPT can be readily upgraded to the medium-range WPT by adding the compensation for resonance. This magnetic resonant WPT is widely recognized as the most effective solution for the near-field WPT with superior system performance. This review mainly focuses on the magnetic resonant WPT as it takes more competitive advantages in power capacity, energy efficiency, flexibility and security over other WPT techniques or wired power transmission.

Progressive commercialization of WPT technologies will be capable of realizing the science fiction scenes of stationary wireless charging [26], move-and-charge [27-29] and fly-and-charge [30, 31]. Nevertheless, the round-trip efficiency is only 70%~80% for each charging-and-discharging cycle of rechargeable batteries [32]. To avoid an additional stage of energy conversion, direct-drive schemes can be regarded as one of the most effective solutions [14, 33] which can link the applications with wireless powers directly. Also, to satisfy the requirements of multiple energy forms, the WPT systems had better support the diversity of energies rather than a single form of electric energy [34-36]. Very recently, the state-of-the-art WPT technologies embrace four directions: (1) advanced modulations; (2) promising applications; (3) informatization and intellectualization; and (4) energy market. Consequently, they will be upgraded to become the smart WPT systems and bring more intelligent experiences for users [5, 37, 38].

A critical classification map of smart WPT technologies is presented in Fig. 1, which includes five main branches – wireless energy modulation, wireless energy conversion, wireless energy intellectualization, wireless energy internet (EI) and wireless energy trading. The concepts of wireless energy and wireless power are mainly differentiated by the definitions of energy and power. Firstly, the wireless energy modulation advocates to regulate the features of pulse sequences and therefore manage the wireless energy purposely. It serves to fulfill the control requirements and improve the system performances [39-41]. Secondly, the wireless energy conversion reveals some emerging schemes enabling direct conversions of multiple energy forms, such as the electrical, chemical, optical, thermal and mechanical energies [42]. These different forms of direct energy conversions are termed wireless charging, wireless lighting, wireless heating and wireless motoring, respectively. Thirdly, wireless energy intellectualization comprises wireless energy security, wireless energy versatility and wireless energy multiple-input multiple-output (MIMO). With the help of cryptography, wireless energy security is guaranteed by using the wireless energy encryption [43] and wireless energy-on-demand [44], thus creating the theftproof WPT systems. Wireless energy versatility enriches the diversities and new functions for the smart WPT. Wireless energy MIMO shapes the magnetic fields for wireless power orientation. Fourthly, wireless EI is to envision a prospective development direction for smart WPT. Superior to wireless energy charger and exchanger, the wireless energy router (WER) supports to download (or deposit), upload (or withdraw) and forward (or transfer) the wireless energy packets for multiple users. Also, the wireless energy architecture is planned to upgrade the framework of power grids incorporated with the increasing penetration of WPT, which is elaborated to design the wireless energy facilities in the field of civil engineering [14, 18]. Fifthly, based on the wireless EI, wireless energy trading [17, 45] will provide a transaction platform supporting the profit-pursuing market activities among peers, communities and internets. Besides the vehicle-to-vehicle (V2V) and vehicle-to-grid (V2G) operations [46], the vehicular community will directly coordinate with the wireless EI to stabilize the power quality by trading their energy. All these five branches form the backbone of smart WPT which will grow more branches with technological progress.

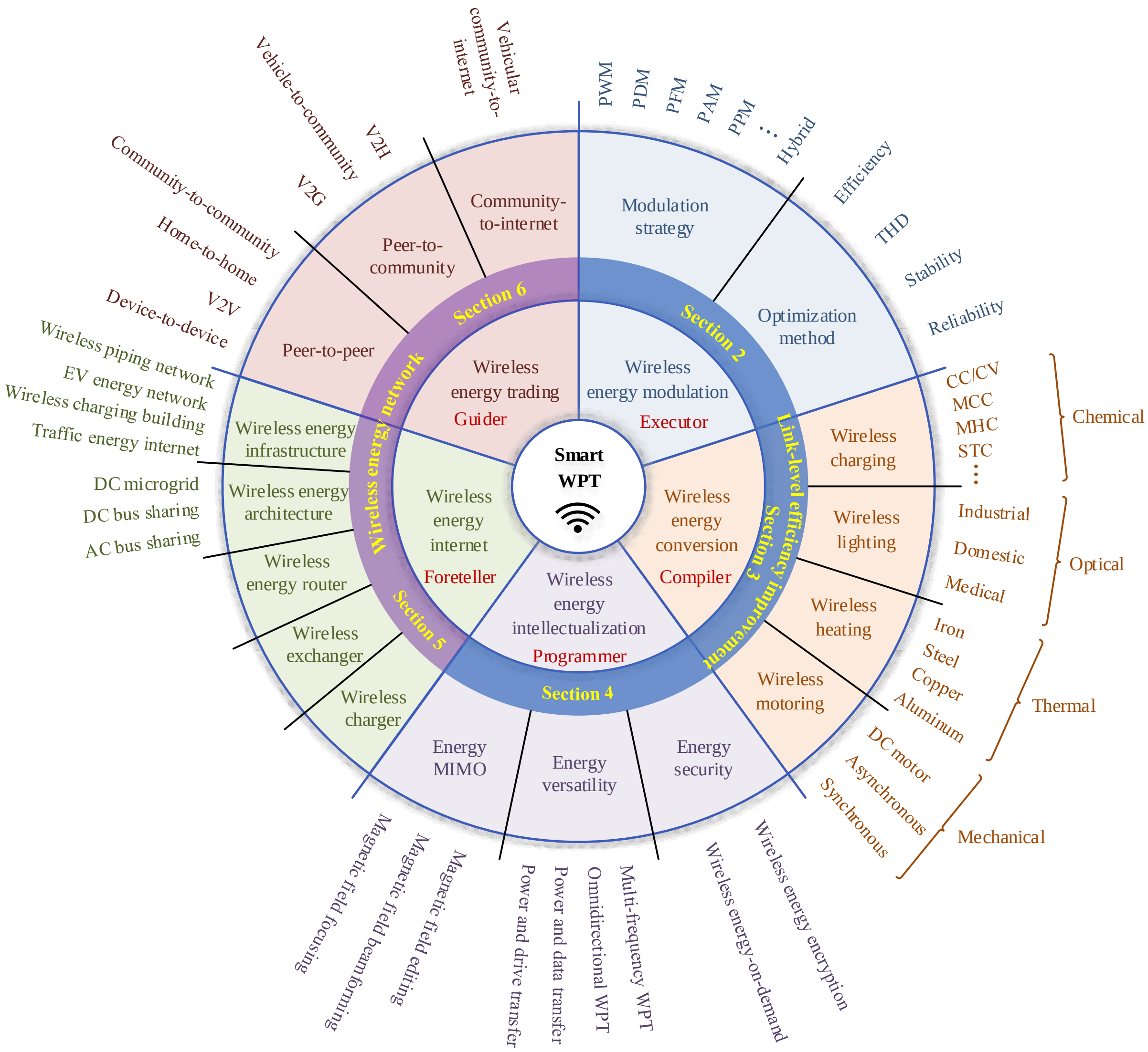


Fig. 1. Critical classification of smart wireless power transfer.

The smart WPT fundamentally differs from the conventional WPT because it synergistically integrates modulation, conversion, intellectualization, internet and trading into WPT to meet the ever-increasing demand of our modern society and human life [5, 42]. The correlations among the above five branches will be sorted out as follows: 1) Wireless energy modulation is the cornerstone of smart WPT which is capable of directly manipulating the wireless powers for the other four branches; 2) Wireless energy conversion serves for the layer of typical applications and involves various modulation strategies to satisfy the practical requirements; 3) Wireless energy intellectualization adds the intelligence to the wireless powers which are confidential, versatile and programable, thanks to the magnetic field modulation and shaping; 4) Wireless EI can be regarded as one promising development trend of smart WPT whose inclusiveness will benefit the cooperation among different branches; 5) Wireless energy trading is based on wireless EIs and guides prosumers to get arbitrage and earn profits. Meanwhile, it develops the energy economics and modulates the power flows to complete both the router energy management and the internet energy distribution.

The rest of this review is organized as follows. Section 2 will discuss the typical modulation strategies and optimization methods. Section 3 will survey different types of wireless energy conversion and their application prospects. Then, Section 4 will present the methodologies, opportunities and challenges of wireless energy intellectualization. In Section 5, wireless EI will be investigated and envisioned in terms of framework, principle and schematic. In Section 6, wireless energy trading will be elaborated by three types of trading: peer-to-peer (P2P), peer-to-community (P2C) and community-to-internet (C2I). Finally, conclusions will be drawn in Section 7. This paper mainly comprises two parts: One is for the link-level efficiency improvement of WPT including Section 2 (wireless energy modulation), Section 3 (wireless energy conversion) and Section 4 (wireless energy intellectualization), and the other is for wireless energy networks including Section 5 (wireless energy internet) and Section 6 (wireless energy trading).

2. Wireless Energy Modulation

Modulation strategies can be regarded as the executor enabling various functionalities. It is borrowed from communication technologies and applied in power electronics. Wireless energy modulation is controlling switches in the inverter or converter for modulating the features of wireless energy, such as frequency, amplitude, orienting direction and functionality. Its purpose is to directly manipulate wireless energy so as to facilitate the implementation of all WPT schemes. Differing from information modulation, energy modulation can achieve not only simultaneous wireless power and information transfer but also more functionalities, such as wireless power control with efficiency improvement, wireless energy selectivity and security, and wireless energy conversion. Practical applications usually require the wireless power control via wireless energy modulation, such as battery charging management, lamp dimming control or motor speed control, rather than stabilized at a highest or rated transmission power. The modulation strategies can be classified into five main branches including (1) pulse width modulation (PWM), (2) pulse density modulation (PDM), (3) pulse frequency modulation (PFM), (4) other modulation strategies (such as pulse amplitude or position), and (5) hybrid modulation. On top of modulation strategies, various optimization methods are developed to improve the system performance for the smart WPT.

2.1. Modulation Strategies

2.1.1. Pulse Width Modulation

The PWM is most commonly used in power electronics for power conversion and control, electric drive and carrier communication [47-49]. Its basic principle is shown in Fig. 2(a), where the phase-shift control (PSC) is typically used for wireless charging. The main pros, cons and applications are summarized in Table 1. The power management of wireless charging is preferable to adopt soft-switching technologies, such as zero-voltage switching (ZVS) [47]. Such ZVS technology deserves to be promoted for advanced power electronics involving silicon-carbide (SiC) or gallium nitride (GaN) field-effect transistors (FETs).

2.1.2. Pulse Density Modulation

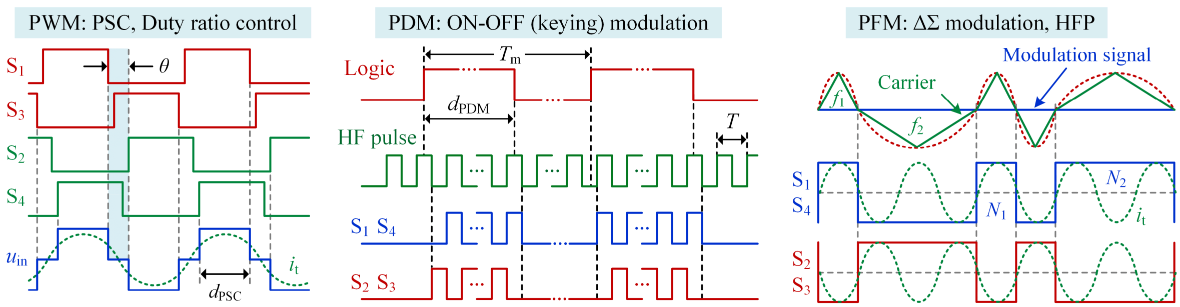
The PDM has been actively developed in power electronics, in particular for the WPT [50] and resonant converters [51, 52]. Its basic principle is shown Fig. 2(b), which includes the ON-OFF (keying) modulation and band-band control with the high-frequency pulse. In Table 1, the PDM can effectively reduce the switching frequency and loss, whereas it will generate relatively large fluctuations on outputs. In addition, it was used to implement the maximum energy efficiency operation [53]. The PDM is one of the most effective solutions for high-frequency wireless energy modulation while maintaining high efficiency.

2.1.3. Pulse Frequency Modulation

The PFM was newly explored for WPT recently [54]. Its typical representations are the delta-sigma ($\Delta\Sigma$) modulation [55, 56] and the hybrid frequency pacing (HFP) [40]. The $\Delta\Sigma$ modulation is a passive method, while the HFP is an active method and more straightforward to generate the desired output. Both methods should be dated back to the technique of quantum resonant converter [57]. The basic principle of ZVS-PFM is shown Fig. 2(c). Interestingly, this new PFM is recognized as a promising alternative for power control, thanks to its “REAL” merits as listed in Table 1. It can improve the whole-process energy efficiency. Very recently, an improved Σ-Δ HFP was designed to effectively reduce the computational complexity [58]. This new PFM was also actively tried in the emerging areas of wireless energy trading [17] and magnetic field editing [59]. Fig. 3 shows the perspectives on conventional efficiency and proposed energy efficiency for clear differentiation. The energy efficiency η_e can be defined as

$$\eta_e = \frac{\sum \left(P_{\mathrm{out}k} t_k \eta_k \right)}{\sum \left(P_{\mathrm{out}k} t_k \right)} \times 100\% \tag{1}$$

where k is the discrete step number; $\eta_k = P_{\mathrm{out}k}/P_{\mathrm{in}k}$ is the definition of conventional efficiency; $P_{\mathrm{out}k}$ is the output power; and $P_{\mathrm{in}k}$ is the input power. It indicates that the optimization of energy efficiency should maximize the efficiencies at high energy points in Fig. 3(b), rather than at the high power points in Fig. 3(a).

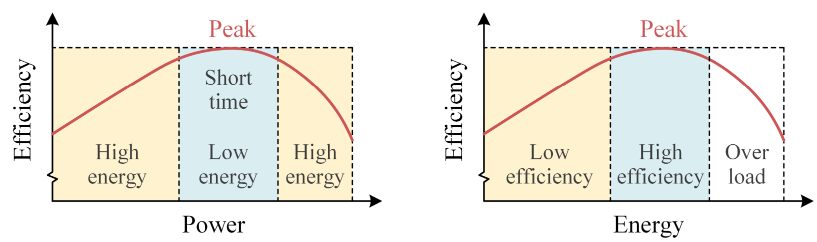


Duty ratio control for half-bridge inverter
(a)

Band-band control with high-frequency pulse
(b)

$d_{\mathrm{PFM}} = N_1/(N_1+N_2)$
(c)

Fig. 2. Typical strategies for wireless energy modulation. (a) PWM. (b) PDM. (c) PFM (or HFP).



(a) (b)

Fig. 3. Perspectives on efficiencies. (a) Conventional efficiency. (b) Proposed energy efficiency.

2.1.4. Other Modulation

Other modulation strategies can be recognized as minority, namely the pulse amplitude modulation (PAM) [60, 61], pulse position modulation (PPM) [62, 63], pulse code modulation [64] and so on. All these modulations were developed for wireless communication technologies in the beginning. Further explorations deserve to be conducted in the field of wireless energy modulation. In Table 1, the advantages, disadvantages and main applications are summarized for two typical modulation strategies. Both the energy modulation [65, 66] and energy coding [67-69] are actively explored to enable the simultaneous wireless information and power transfer, which are the typical applications in the regime of RF-WPT.

2.1.5. Hybrid Modulation

Hybrid modulation usually integrates two or several modulation types, thus possessing the merits of different strategies. First, wireless energy encryption adopted the PFM and PDM for encoding energy packets [70]. Second, the frequency-duty-ratio control can be regarded as a hybrid modulation of PFM and PWM for EV chargers [71]. Third, a new hybrid modulation was designed by integrating the PDM and PFM skillfully to improve the efficiency and applicability within wide input and output ranges [72]. In Table 1, the hybrid modulation can optimize the system performances and satisfy more functional requirements via software algorithm rather than hardware implementation. Modulation strategies can help save more electronic components while improving energy efficiency effectively. Hence, more hybrid modulation strategies await to be explored and will exhibit more competitive advantages in the next decade(s).

For wireless energy modulation, the transfer distance is 100~200 mm or longer, and the system efficiency can reach 92%~95%. Enlarging the coupler can further improve the distance and efficiency. During wireless power control, the PFM can not only improve the system efficiency by 7%~18% [40, 58] as compared with the PWM but suppress the output fluctuations by around 50% as compared with the PDM.

Table 1. Critical comparison of various modulation strategies.

Modulation strategies		Pros	Cons	Applications
PWM		✓ Easy for implementation ✓ Superior applicability ✓ High control precision ✓ Mature technology	× Constant switching frequency × High switching loss × Involve even-order harmonics for half-bridge inverters if the duty ratio is below 50% × Require soft-switching technique for high-frequency applications	• Wireless charging [26, 47] • Power conversion [48] • Motor drive [49] • Communication
PDM		✓ Easy for implementation ✓ Reduce switching frequency ✓ Suppress switching loss	× Low control precision × Large output fluctuation	• Wireless charging [50, 53] • Power conversion • Resonant converter [51, 52]
PFM		"REAL" merits: ✓ Robust soft switching ✓ Eliminate even-order harmonics ✓ Alleviate switching loss ✓ Lower switching frequency	× Relatively complex algorithm × More suitable for high-frequency applications	• Wireless charging [54, 58] • Wireless lighting [85] • Wireless motoring [14, 33] • Magnetic field editing [59] • Resonant converter [40]
Other	**PAM**	✓ Easy for implementation ✓ Easy for modulation and demodulation ✓ Reduce bandwidth requirement	× More noise × Require more power × Low power efficiency	• Wireless communication [60] • Power electronics [61]
	PPM	✓ Better noise immunity ✓ Less noise interference ✓ Constant transmission power	× Require synchronization pulse × Require large bandwidth × Complex for modulation and demodulation	• Air traffic control • Wireless communication [62, 63] • Data compression
Hybrid		✓ Integrate merits of different modulation strategies ✓ Realize multiple functions ✓ System optimization by software	× Add complexity of algorithm × Complex for implementation	• Wireless charging • Wireless energy encryption [70] • Efficiency optimization [72]

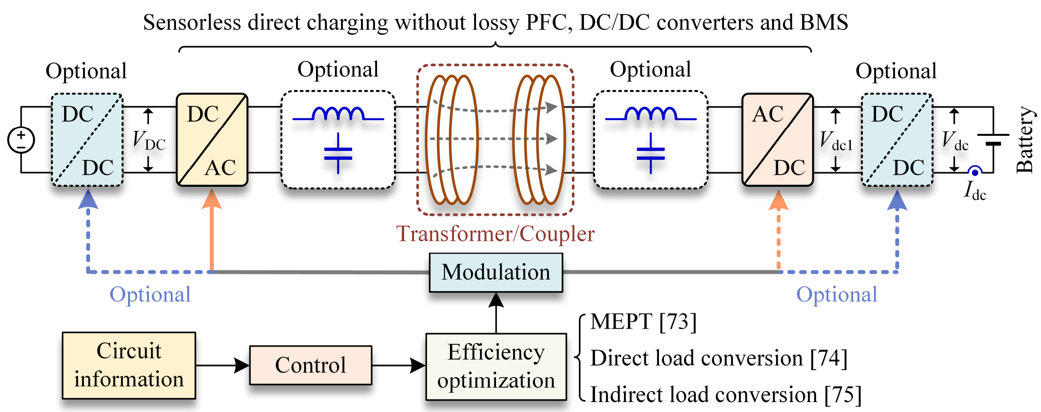


Fig. 4. Energy efficiency optimization using wireless energy modulation.

2.2. Optimization Methods

In addition to the total harmonic distortion (THD), stability and reliability, energy efficiency is a key performance indicator for wireless energy modulation. Thus, the efficiency optimization can contribute to maximizing the energy efficiency for the whole process rather than a specific operating point. Fig. 4 shows three mainstreams of efficiency optimization methods: (1) maximum efficiency point tracking (MEPT), (2) direct load conversion, and (3) indirect load conversion. First, the MEPT usually utilizes the perturbation and observation of system power or efficiency in real-time for maximizing the energy efficiency [73]. Second, the direct load conversion [74] uses the modulation method to directly modify the load for optimizing the energy efficiency. Third, the indirect load conversion [75] directly controls the input-output characteristics to indirectly modify the load, thus improving the energy efficiency. In addition, wireless direct charging technology can avoid the use of lossy power factor correction (PFC) converter, direct-current (DC)/DC converters, and battery management system (BMS), thus improving the whole-process energy efficiency. Wireless energy modulation, such as the PFM, is eligible for the energy conversion and management in the direct charging technology. This modulation-based direct charging technology is high-efficiency, economical, and environment-friendly with fewer power components for battery charging.

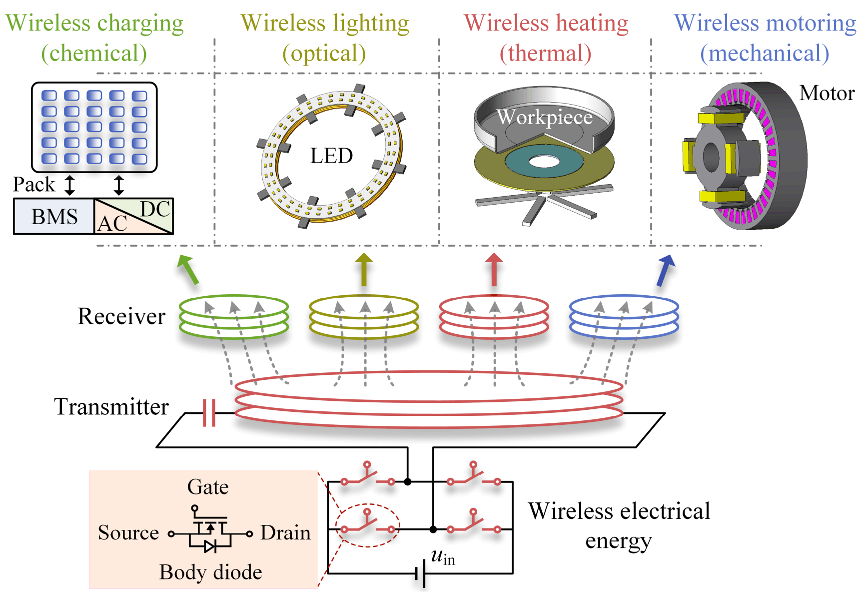


Fig. 5. Wireless energy conversion for different application purposes.

3. Wireless Energy Conversion

For different purposes in practical applications, wireless electrical energy is usually required to be converted to other forms of energy, such as chemical, optical, thermal and mechanical energies. As shown in Fig. 5, the wireless energy conversion can be classified into four parts including (1) wireless charging, (2) wireless lighting, (3) wireless heating, and (4) wireless motoring. Besides, the wireless energy conversion to talkative acoustic energy can be referred to the relevant technologies of wireless communication or wireless power and data transfer.

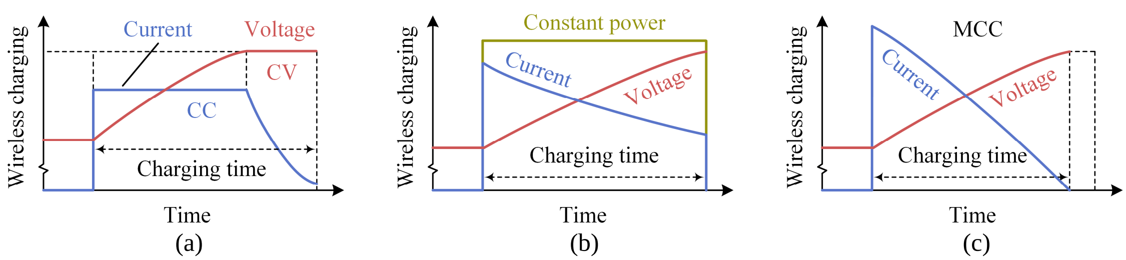


Fig. 6. Typical charging control methods. (a) CC/CV mode. (b) Constant-power mode. (c) MCC mode.

3.1. Wireless Charging (Chemical)

Wireless charging is to convert the electrical energy to chemical energy stored in the battery pack. Such wireless charging can be divided into several typical control modes, namely (1) constant-current (CC)/constant-voltage (CV) charging [17, 76], (2) constant-power charging [77], (3) minimum loss charging [78], and (4) maximum current charging (MCC). Accordingly, Fig. 6 shows the principles of these typical charging modes, and the principle of newly proposed MCC is shown in Fig. 6(c). On the one hand, by incorporating a data-driven electro-thermal battery model, the MCC, most healthy charging (MHC), or shortest time charging (STC) deserves to be investigated and applied in the whole charging process. The development of STC can accelerate the charging speed, while that of MHC can maximize the battery cycle life. On the other hand, the bidirectional charging control enables the peer-to-peer charging, wireless energy exchanging and wireless energy trading of V2V, vehicle-to-home (V2H) and V2G [46]. Nonetheless, energy density and safety are still the main concerns and challenge the current chemistry of lithium-ion batteries (LIBs) [79]. Besides, wireless sensorless charging is recommended to eliminate all sensors at the receiver side in Fig. 4, and it will be one of the most promising research directions in the near future.

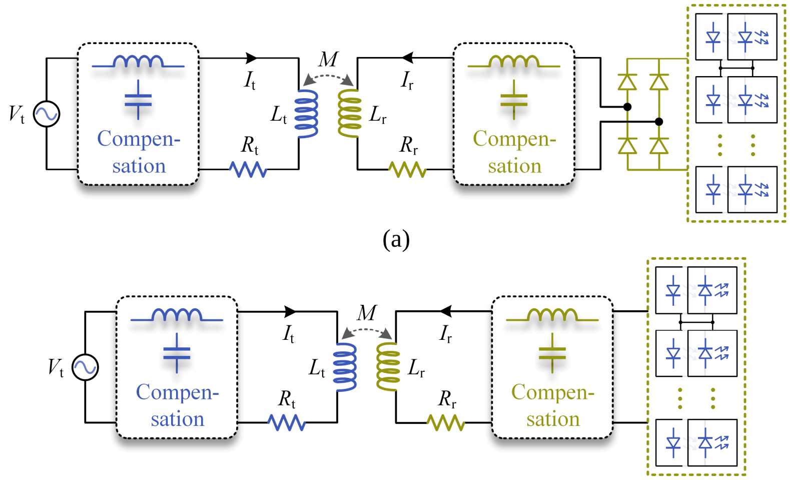


Fig. 7. Wireless lighting using LEDs. (a) DC drive. (b) AC drive.

3.2. Wireless Lighting (Optical)

Wireless lighting is to convert the electrical energy to optical energy for various applications including (1) industrial scenarios, (2) domestic scenarios, and (3) medical scenarios [80]. First, thanks to the advantages of high luminous efficacy and long service life, high-intensity discharge (HID) lamps have been widely used for indoor or outdoor lighting purposes. The wireless lighting scheme for HID lamps can directly use the resonant voltage of WPT for ignition, thus avoiding the use of a bulky ballast [81]. Wherein, the wireless lighting of fluorescent lamps and metal halide lamps was mainly developed for indoor lighting. In contrast, the wireless lighting of low-pressure sodium lamps and high-pressure sodium lamps was mainly developed for outdoor applications, such as for street lighting. Significantly, the wireless HID lighting shall work at a proper frequency band to alleviate the acoustic resonance phenomenon that will destabilize the lamp arc. Second, the light-emitting diode (LED) lamps are superior to the HID lamps and will gradually dominate the lighting market from now on [82]. Hence, wireless LED lighting was actively developed. Fig. 7 shows the system topologies of wireless LED lighting including the DC drive LED [83, 84] and alternating current (AC) drive LED [85]. The high-order network was designed to serve the CC drive for LEDs, and the PFM control was explored for improving the whole-process energy efficiency during the LED dimming. Third, in addition to the industrial and domestic lighting purposes, the wireless-controlled LED scheme was also investigated for medical applications, in particular for deep brain stimulation [80].

3.3. Wireless Heating (Thermal)

Wireless heating is to convert the electrical energy to thermal energy for various heating purposes. Conventional induction heating has been well developed by using the magnetic inductive coupling [35], and it can be recognized as a kind of wireless heating. Recently, the mechanism of magnetic resonant coupling was investigated for flexible wireless heating [86]. Figs. 8(a)–8(c) show the equivalent circuits, eddy current density and Joule loss density of wireless heating, respectively. Such wireless heating using the magnetic resonant coupling was further developed to realize the homogenous heating effect [87] and heat all-metal workpieces, including iron, steel, copper, and aluminum. Also, it can be readily extended for all-utensil heating for both the ferromagnetic, non-ferromagnetic and even non-conductive appliances.

Nonetheless, the real-time detection and control challenge the wireless heating system unless an artificial intelligence (AI) method is adopted to identify the metal types, workpiece position and optimal resonant frequency [88].

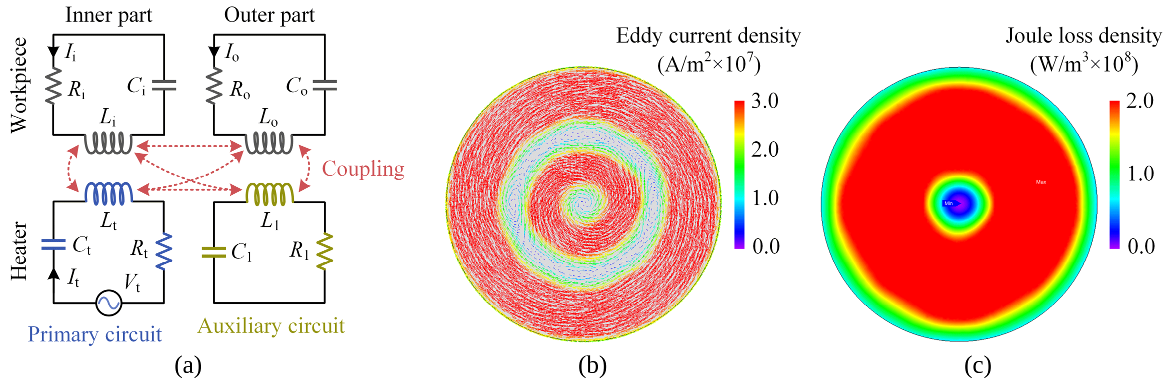


Fig. 8. Wireless heating. (a) Equivalent circuits. (b) Eddy current density. (c) Joule loss density.

3.4. Wireless Motoring (Mechanical)

Wireless motoring is to convert the electrical energy to mechanical energy for various motor drive applications. Intrinsically, conventional electrical machines have integrated the WPT technologies with a millimeter air gap between its stator and rotor, and they convert and deliver the electrical energy to mechanical energy wirelessly. Nonetheless, the power cables could be fragile in harsh environments, and the battery performance is by no means satisfactory for durable cruising. Thus, the portability and applicability of electric motors are highly sacrificed. Accordingly, various wireless motors emerged for solving these problems. The types of wireless motors include (1) dual-controller wireless motor, (2) wireless DC motor, (3) wireless induction motor (IM), (4) wireless switched reluctance motor (SRM), and (5) wireless synchronous motor. Particularly, literature [89] can be recognized as a landmark for predicting the use of WPT for EVs. This trend is leading more researchers to study more technical strategies that can offer high-performance solutions.

3.4.1. Dual-Controller Wireless Motor

As a combination of wireless charging and motor drive, the dual-controller wireless motor used one central controller and one motor controller located at the transmitter and receiver sides, respectively [90]. Thus, double-side wireless communication modules were employed inevitably. Accordingly, a simplified configuration of the dual-controller wireless motor system is shown in Fig. 9. Wherein, the central controller is to control the power inverter, while the motor controller is in charge of energy conversion. Importantly, all existing motors and control strategies are available in this system. Thus, this system has wide applications, from medical implants to EV in-wheel motors. However, both the controller and inverter require some peripheral circuits that are quite complicated and sensitive to the high voltage and high current. Hence, such a dual-controller wireless motor might not be eligible for totally isolated environment.

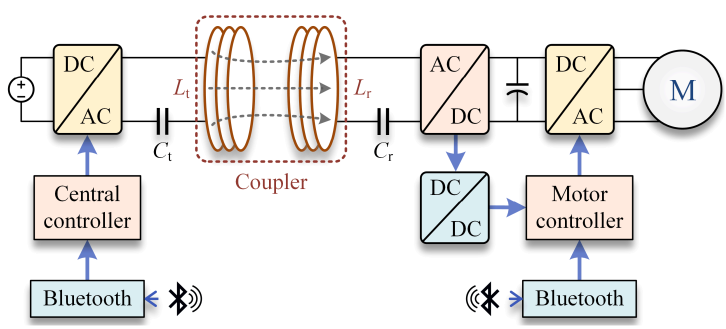


Fig. 9. System configuration of dual-controller wireless motor.

3.4.2. Wireless DC Motor

The wireless DC motors were actively developed in two types including (1) wireless permanent magnet (PM) DC motor, and (2) wireless bidirectional DC motor, as shown in Fig. 10. On the one hand, the PM DC motor can be minimized for medical implants. Fig. 10(a) shows the simplified system configuration of a wireless PM DC motor whose structure is simple but robust and suitable for maintenance-free environment [33]. Also, the variable voltage control can be readily applied for speed regulation of this wireless motor. On the other hand, the wireless bidirectional DC motor enables the bidirectional motion capability, but the use of controlled switches increases the system complexity, as shown in Fig. 10(b) [91]. The transmitter can charge the targeted receiver by frequency selection, while the non-targeted receiver receives nothing. Accordingly, the DC motor can be fed by the targeted receiver and is able to rotate in the aimed direction. As a self-drive system, the control signal can be extracted from the wireless energy received at the receiver side. After isolating, rectifying and filtering through the transformer, diode and capacitor, respectively, the desired control signal can be generated stably.

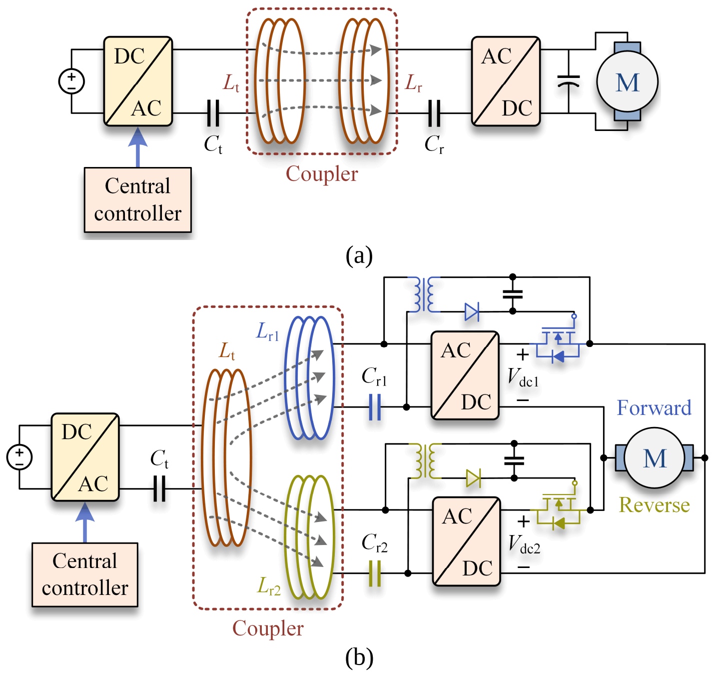


Fig. 10. System configurations of wireless DC motor. (a) Wireless PM DC motor. (b) Wireless bidirectional DC motor.

3.4.3. Wireless Induction Motor

Wireless IMs can be classified into three mainstreams: (1) single-phase wireless IM, (2) three-phase wireless IM, and (3) multi-phase wireless IM. Moreover, the single-phase wireless IM has been actively developed in two types: (i) controller-based wireless IM, and (ii) controller-less wireless IM. Because the single-phase IM has the advantages of high reliability and low cost, it has been widely used in both the industrial and domestic applications, such as for ventilation fans. First, a scheme of controller-based wireless IM was investigated in Fig. 11(a) [34]. The double-frequency synthesized PWM was implemented at the transmitter side, and it delivered the high-frequency AC power for WPT and the low-frequency AC power for motor drive. A controller can control the chopper to demodulate the wireless power for motor drive. Second, a controller-less wireless shaded-pole IM was designed in Fig. 11(b) [92], which involved two inductor-capacitor (*LC*) circuits to self-drive the motor converter at the receiver side. It can be totally sealable with the merits of electrocution-free and wide applicability. Besides the shaded-pole IMs, other single-phase IMs such as the split-phase IM, capacitor-type IM and hysteresis IM can readily be applied. Third, three-/multi-phase wireless IMs have not been specially designed yet. The main reason is that three-/multi-phase AC current cannot be easily acquired without the use of controllers. Nonetheless, the three-/multi-phase IMs can provide better dynamic performances and bidirectional motions, and they will be more applicable than other motors once the fragile control module is eliminated at the receiver side.

3.4.4. Wireless Switched Reluctance Motor

Thanks to the merits of robust structure, low manufacturing cost, and outstanding torque-speed characteristics, the SRMs have been recognized to exhibit considerable potentials than other motors. The wireless SRMs can be mainly classified into two types: (1) three-phase wireless SRM, and (2) multi-phase wireless SRM (such as four-phase or five-phase). Fig. 12 shows the simplified system configuration of three-phase wireless SRM, where three receivers with different resonant frequencies were deployed for feeding the three-phase motor windings one by one [93]. By incorporating the rotor position feedback, the single transmitter can selectively charge the targeted receiver and motor winding in a desired sequence, which does not need any controller at the receiver side. All modulation strategies (especially PFM) can be used for speed regulation of this wireless SRM. Similar to the three-phase wireless SRM, other multi-phase wireless SRMs [94] can also be readily implementable. For example, each stator winding is fed by a receiver, as shown in Fig. 12.

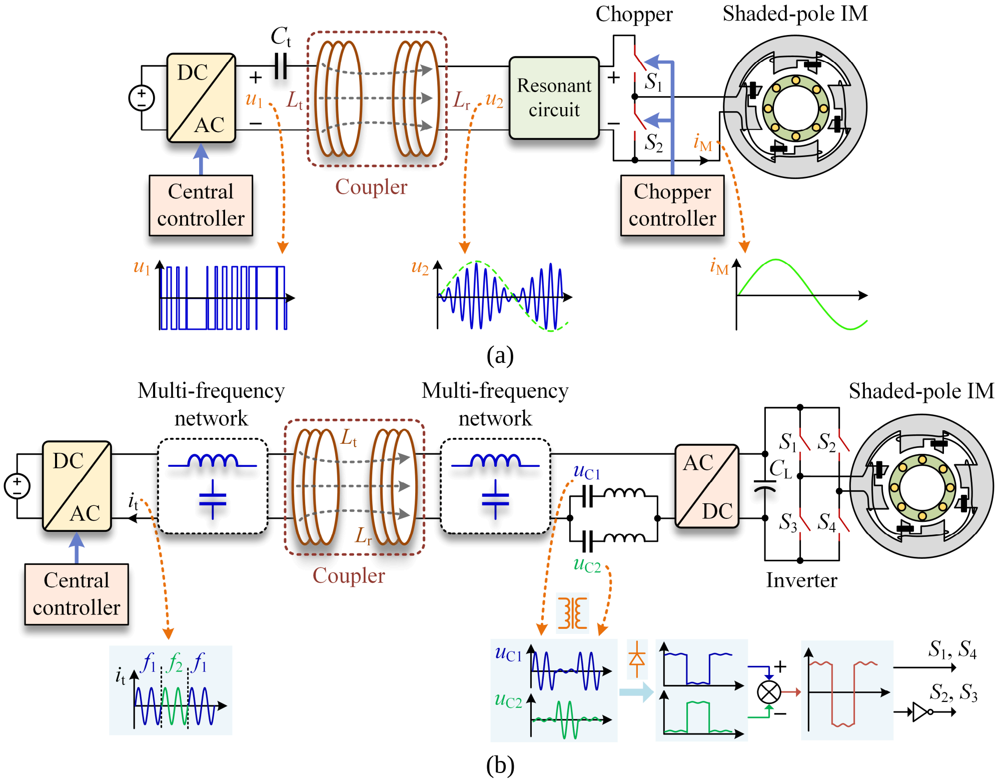


Fig. 11. System configurations of wireless single-phase IM. (a) Controller-based wireless IM. (b) Controller-less wireless IM.

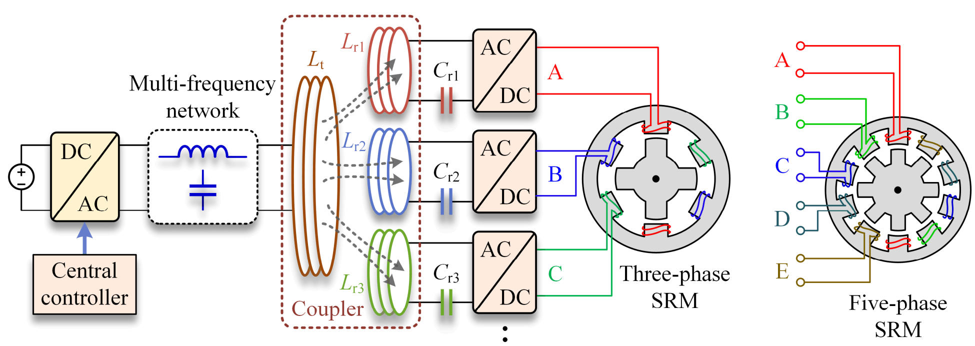


Fig. 12. System configuration of wireless SRM.

3.4.5. Wireless Synchronous Motor

To overcome the limitations of rotor PM synchronous motors (PMSM), such as accidental demagnetization, the WPT has been recommended for the field winding excitation. In Fig. 13, both the inductive power transfer (IPT) [95] and capacitive power transfer (CPT) [96] have been actively investigated for wireless synchronous motors with an electrically excited rotor. In this kind of electrically excited synchronous motors, the wireless excitation method would have no sparking hazard, better convenience and higher flexibility, and the constant-torque operating range can be extended by regulating the magnetic flux. Besides, all existing synchronous motor types, namely the brushless DC motor and brushless AC motor, are suitable for this kind of wireless synchronous motors. Both the IPT and CPT can readily achieve over 93% efficiency [95, 96] when feeding the rotor windings. The implementation of CPT is suitable for rotational scenarios, while the power density of the IPT coupler is much greater than the CPT coupler. Therefore, the IPT might be more promising in the next decade(s) [97].

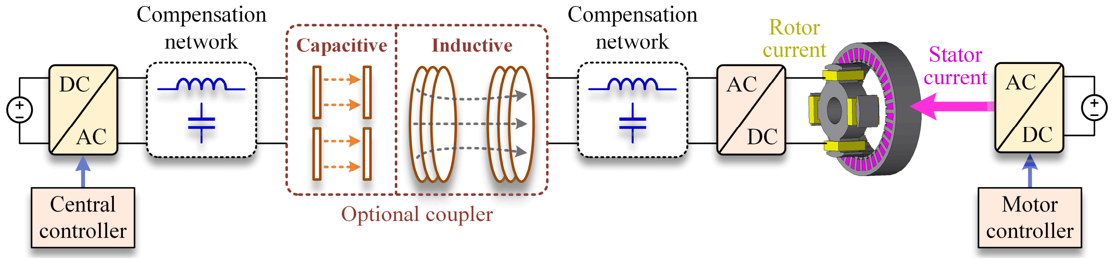


Fig. 13. Electrically excited synchronous motor using WPT for inner rotor.

Table 2. Critical comparison of wireless motor systems.

Aspect	Topology	Pros	Cons	Applications
Dual-controller wireless motor	• Cascading the traditional motor at the receiver side	✓ Simple for implementation ✓ Available for all motors and control strategies ✓ Wide range of applications	× Use of controller and converter at receiver side	• Hub motor for EV
Wireless DC motor	• Single receiver for unidirectional DC motor • Double receivers for bidirectional DC motor	✓ Simple control ✓ Controller-less at receiver side for bidirectional DC motor	× Use of carbon brushes	• Implantable medical device • Underground drainage system
Wireless SRM	• Each receiver feeds one-phase stator winding	✓ Controller-less at receiver side ✓ Available for bidirectional motion	× Use of multi-receivers × Require position detection module	• Hub motor for EV • Cleaning pig
Wireless IM	• Single receiver • Self-drive circuit is used to replace motor controller	✓ Simple control ✓ Single receiver	× Use of converter or AC chopper at receiver side	• Submersible sewage pump • Wireless piping network
Wireless SM	• Feeding rotor winding via WPT • Feeding stator winding via wire	✓ Regulable rotor flux ✓ No risk of demagnetization	× Not suitable for sealed environment	• Hub motor for EV

3.4.6. Development Trends

A critical comparison of wireless motor systems is given in Table 2 for assessing some key features including the topologies, pros, cons and potential applications. In the future, the developments of wireless motors trend to improve the robustness at the receiver side and the dynamic performance of motor drives. Three research directions, namely (1) wireless controller-less motor, (2) wireless converter-less motor, and (3) wireless sensorless motor, are identified and deserve to be discussed as follows. The control module, passive components and active switches suffer from inherent drawbacks, such as bulky structure and the need for regular maintenance. Thus, the development of a wireless controller-less motor can increase the system efficiency and robustness. Recently, a coreless and magnetless electric motor was developed by using the WPT to directly drive the rotor and reduce the iron loss [98]. Besides, a three-phase WPT system [99] was studied by employing the envelope detector to offer the three-phase AC currents, which can be promisingly extended for developing a three-phase wireless motor, termed wireless converter-less motor. To achieve the reliable control for wireless motors, the position or speed feedback is almost indispensable. However, the position encoder and wireless communication module are costly and bulky [100]. Hence, the development of a wireless sensorless motor is very attractive, though it is quite challenging on how to observe the required motor parameters in the transmitter only.

The tethered high-power machines significantly sacrifice the flexibility of rotation and locomotion. The cable wear-off, multi-stage power converters and fragile microcontrollers are inevitable, thus decreasing the system performance and increasing the risk of faults. Apart from delivering electricity wirelessly, the WPT can drive the high-power machines for direct energy conversion, thus experiencing less lossy power conversion, improving the system performance and robustness, and reducing the system complexity. Future high-power machines can be totally sealed in an all-in-one wireless machine system that has spark-free, electrocution-free and maintenance-free advantages. Such wireless high-power machines can be controlled wirelessly and operate flexibly in harsh or enclosed environments such as underearth, underwater and explosive atmospheres. With technical breakthroughs, wireless high-power machines will be more promising to integrate more advantages of WPT. Interestingly, the WPT can wirelessly deliver electricity for superconducting electric excitation for ultrahigh-power rotating machines.

4. Wireless Energy Intellectualization

4.1. Wireless Energy Security

Wireless energy security gradually became a major concern in the WPT system because the wireless energy is open access for multiple pick-ups, as shown in Fig. 14(a). The WPT technologies enable the wireless energy more convenient to be harvested not only for authorized receivers but also for unauthorized receivers. To guarantee the wireless energy security, two schemes were actively developed, namely (1) wireless energy encryption [43], and (2) wireless energy-on-demand [44]. Their critical comparison is given in Table 3.

Table 3. Critical comparison of wireless energy security.

Wireless energy security	Energy encoding/decoding	Generation of security key	Dimensions of security key	Features
Wireless energy encryption	Transmitter/ Receiver	Transmitter	1D (frequency encryption)	• Ensure energy security by frequency encryption [43] • Discrete energy encryption with finite frequency selections
			2D (FDE)	• Improved energy security by 2D FDE [54] • Continuous energy encryption but within narrow frequency band [101]
Wireless energy-on-demand	Transmitter/ Receiver	Receiver	2D (FDE)	• Customized requirements on power level, frequency and duration [44] • Ensure energy security by 2D FDE

4.1.1. Wireless Energy Encryption

Wireless energy encryption was coined by using a security key of the one-dimensional (1D) chaotic frequency for energy encoding [43]. This 1D frequency encryption is to chaotically encrypt the frequency of wireless energy, while the duration of each encrypted frequency and other candidate parameters are fixed and not encrypted. This security key is used for energy encryption and decryption and will be delivered between the transmitter and authorized receivers securely. Due to the lack of security key, the unauthorized receivers fail to decrypt the wireless energy, thus stealing no power. Wherein, a switched-capacitor array is used to implement the 1D wireless energy encryption [43] by adjusting the frequency discretely. However, the number of switched-capacitor branches is limited, which can generate finite frequency selections only. Because the unauthorized users can dynamically track and lock the encrypted frequency, discrete encryption of finite frequency selections will increase the risk of energy decryption and stealing. Such 1D wireless energy encryption can ensure the wireless energy security. Nonetheless, it suffers from two drawbacks: basic 1D encryption, and discrete encryption with finite frequency selections. On the one hand, a two-dimensional (2D) frequency-and-duration encryption (FDE) was recommended as the chaotic security keys to improve the security [70]. This 2D-FDE is to encrypt both the frequency and its duration chaotically as shown in Fig. 14(b), which can significantly increase the difficulty of energy decryption and better defend the tracking by unauthorized users, thus preventing energy theft and guaranteeing energy security. In Fig. 14(b), only the authorized users can harvest the wireless power, while the unauthorized users pick up nearly no power, thus improving the energy security performance. Besides, a ZVS-PFM was reported to achieve the goals of wireless energy controllability, selectivity and security [54]. On the other hand, continuous wireless energy encryption was developed based on a 2D-FDE [101] with infinite frequency selections to further improve the security, but it still suffers from a narrow frequency band. Next, continuous wireless energy encryption deserves to be further explored with a wider frequency band.

4.1.2. Wireless Energy-on-Demand

Security key is generated from the transmitter in the scheme of wireless energy encryption. However, it should be more preferable to generate the security key from the authorized receivers in Fig. 14(a). Thus, wireless energy-on-demand was developed by using the 2D-FDE, which inherently satisfies the customized requirements on wireless power, frequency and duration [44]. This scheme offers more flexibility while maintaining the energy security for multi-objective WPT systems. Besides, using specific frequencies, both the selective WPT [102, 103] and the multi-frequency (MF) WPT [104, 105] can be regarded as a special kind of wireless energy-on-demand. Each receiver is uniquely assigned with one operating frequency only in the multi-receiver WPT system, while the transmitter will generate the customized wireless powers to satisfy the diverse requirements from targeted receivers.

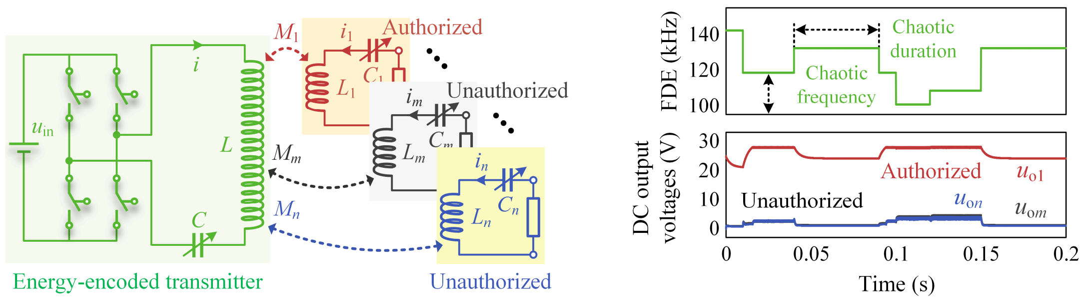


Fig. 14. Wireless energy security. (a) Encrypted WPT with multiple pick-ups. (b) Energy security performance.

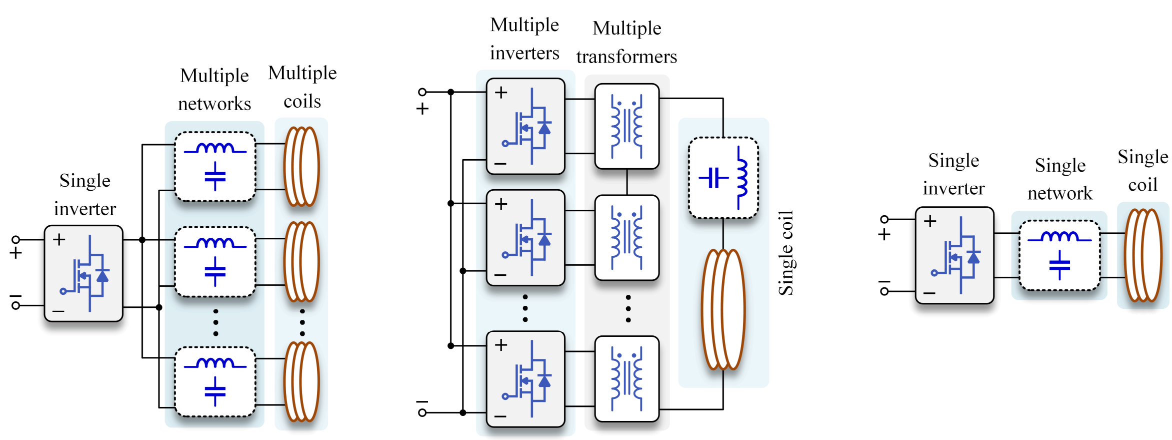


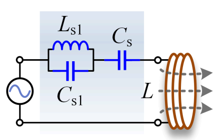
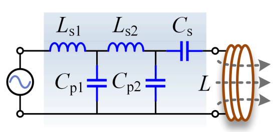
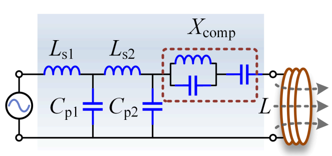
Fig. 15. System configurations of multi-frequency WPT. (a) Single-inverter multi-transmitter topology. (b) Multi-inverter multi-transformer topology. (c) Single-inverter single-transmitter topology.

4.2. Wireless Energy Versatility

4.2.1. Multi-Frequency WPT

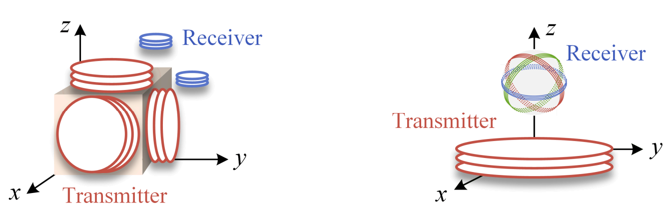
The MF-WPT system can effectively improve the charging applicability and compatibility for multi-standard receivers. The MF-WPT usually requires generating the transmitter currents with two or more frequencies to deliver the MF wireless powers simultaneously. Thus, this system can energize one or multiple receivers. The existing systems of MF-WPT can be divided into three main types: (1) single-inverter multi-transmitter topology, (2) multi-inverter multi-transformer topology, and (3) single-inverter single-transmitter topology. Correspondingly, their system configurations are shown in Figs. 15(a)–15(c), respectively. To power the separate transmitter coils simultaneously in Fig. 15(a), using a single inverter requires the special modulation control [104], which inevitably increases the switching loss and the undesired harmonics, thus reducing the system efficiency. In Fig. 15(b), another scheme uses multiple inverters and multiple transformers to couple the different current components into a single transmitter coil. This type of MF-WPT scheme possesses the advantage of good controllability and independence [105]. However, the use of multiple transformers will bring additional power losses and result in a low system efficiency. To realize the MF-WPT, a well-developed topology is shown in Fig. 15(c) with a single inverter and a single transmitter only [106-108]. To produce multiple frequency channels, two main issues need to be solved: the input voltage should comprise multi-frequency components; and the WPT network shall offer multiple resonant frequencies, and thus the zero-phase-angle operation can be realized in each frequency channel. For the first issue, the most convenient way is to use the inherent harmonics of square waveforms or to use a special modulation by injecting different harmonic components with desired ratios. For the second issue, using the high-order compensation can be recognized as the most effective solution. Different compensation topologies are summarized and compared in Table 4. In addition, another type of MF-WPT system was designed with one special inverter and one single transmitter [109]. This system added two diodes to create different current components in the transmitter, hence enabling the MF-WPT. Its advantage lies in the simplicity and compatibility, but it suffers from additional losses caused by the added diodes.

Table 4. Critical comparison of system topologies for single-inverter single-transmitter multi-frequency WPT.

WPT network	Number of components	Impedance adjustment	Features
	3	Not support	• Simple for implementation • Sensitive to interference • Expandable network [106] • Require special modulation [107]
	5	Support	• Easy for power adjustment [14] • Insensitive to interference • Require no special modulation
	7	Support	• Complex for implementation • Insensitive to interference • Current harmonics in opposite phase and high current stress [108] • Require no special modulation

4.2.2. Omnidirectional WPT

The omnidirectional WPT usually uses the orthogonal coils in either the transmitter or the receiver [110, 111] as well as the orthogonal configurations in both. Two former types of system implementation are shown in Figs. 16(a) and 16(b), respectively. For the orthogonal transmitter, the system can use the phase angle control for transmitter currents, which can realize a rotating magnetic field and thus the uniform omnidirectional power transmission in 2D or three-dimensional (3D) space [112]. For the omnidirectional receiver, the system lacks controllability but with more fault-tolerant capability. Both the shapes of transmitter and receiver coil can be spherical, cubic and so on. Wherein, they can freely adopt the concentrated or distributed coil(s) with the circular, rectangular or hexagon shape.



(a) (b)

Fig. 16. System configurations of omnidirectional WPT. (a) Orthogonal transmitter. (b) Orthogonal receiver.

4.2.3. Wireless Power and Data Transfer

Based on the techniques of MF-WPT systems, different systems are developed to realize simultaneous wireless power and information (or data) transfer (WPIT) at multiple frequency channels [113]. One of the most popular designs uses one single inverter and one single transmitter only to deliver the power and data information concurrently, and two different receivers can extract the wireless power and wireless data independently, as shown in Fig. 17(a) [114]. With a similar principle, an inductive and capacitive combined WPIT system was developed in [115]. Both types of WPIT systems separate the power and signal transmissions, thus having higher system stability and controllability. Besides, it also realized simultaneous power and information delivery through a single coupler, as shown in Fig. 17(b) [116]. This system uses two extra transformers to couple the power and data transmission channel, which can thus cut out the extra data-receiving coil and simplify the WPT system [117]. Owing to the symmetric topology, this WPIT system can flexibly realize a duplex data transmission.

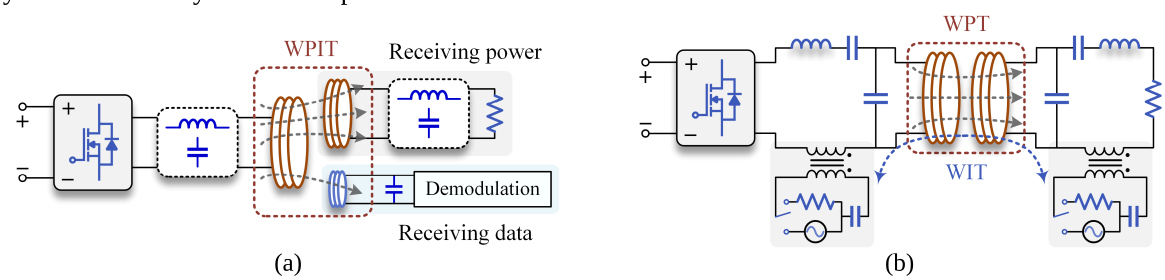


Fig. 17. Wireless power and information systems. (a) Integrate WPT and WIT. (b) Separate WPT and WIT.

4.2.4. Wireless Power and Drive Transfer

Differing from the WPIT system, the new designs of wireless power and drive transfer (WPDT) systems were developed for different practical applications [42], such as for wireless motoring [14, 93, 96], wireless lighting [81, 83-85], and wireless heating [86]. They all can be generalized as the wireless power drive. Accordingly, a typical WPDT system was developed for underground wireless piping networks as shown in Fig. 18 [14]. Its working principle is to modulate the wireless powers and directly utilize the drive capabilities of wireless powers. This system contains two frequency channels (f_p and f_n) to generate the ON and OFF gate signals for driving the power switches wirelessly. This WPDT scheme avoids the use of LIBs with low round-trip conversion efficiency. Also, all the control procedures can be completed by the transmitter signals only, and no extra communication modules are needed for information delivery.

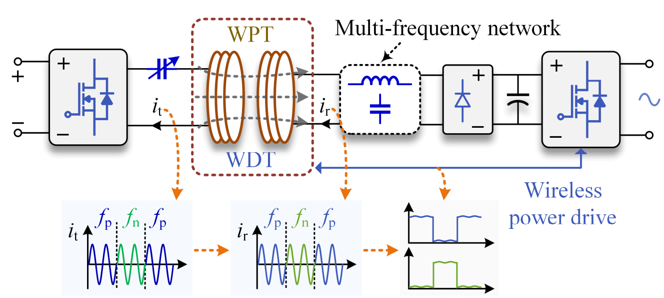


Fig. 18. Wireless power and drive transfer system integrating WPT and WDT.

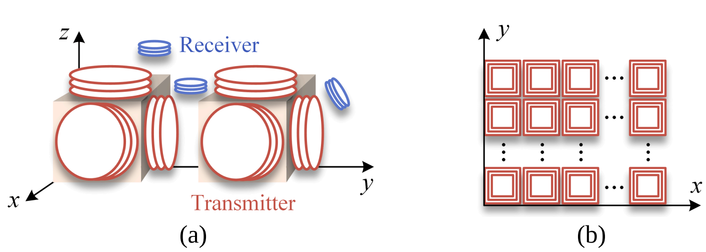
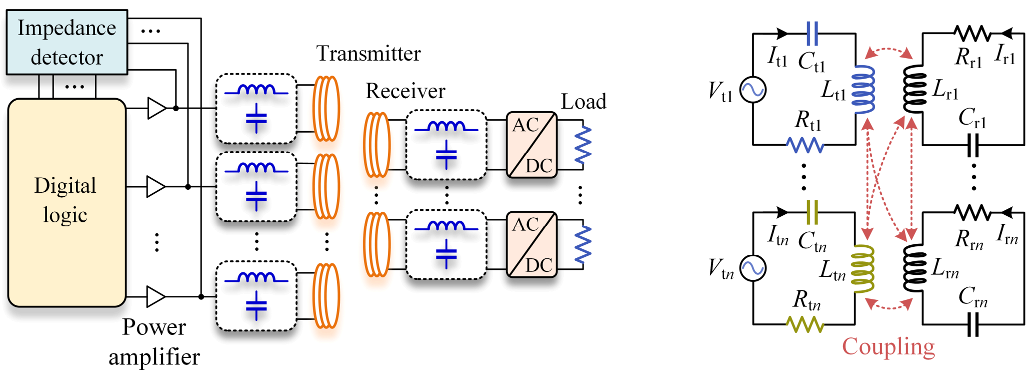


Fig. 19. Typical MIMO WPT systems. (a) Three-dimensional configuration. (b) Flattened configuration.

4.3. Wireless Energy MIMO

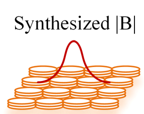
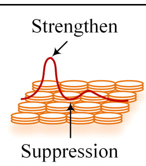
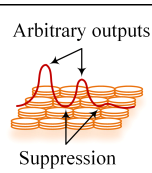
Recently, the MIMO WPT systems have drawn much attention for dynamic power transmission with good controllability and flexibility. Generally, the system configurations can be divided into two main forms: the three-dimensional transmitter system in Fig. 19(a) [118, 119], and the distributed and flattened transmitter system in Fig. 19(b) [120]. With an orthogonal deployment of transmitter coils, the cross-coupling effect can be eliminated, and thus the system has no reactive power. However, the degree of freedom is highly limited. While the latter configuration can provide more flexibility in both the control and optimization. Fig. 20 shows the general configuration of the MIMO WPT system. According to the functions and purposes, the wireless energy MIMO systems mainly include (1) magnetic field focusing (MFF), (2) magnetic field beamforming (MFB), and (3) magnetic field editing (MFE). Their different implementations and features are summarized and compared in Table 5. Wherein, a linear model specifies the linear relationships between a dependent variable and independent variables, while a non-linear model describes nonlinear relationships. For example, because the relationship between the magnetic field and the transmitter currents is linear, the MFF model is regarded as a linear model. In contrast, the relationship between the power and the transmitter currents is quadratic. Also, both the optimization objective and constraint conditions are quadratic. Hence, the MFB model is regarded as a non-linear model.



(a) (b)

Fig. 20. General configuration of MIMO WPT system. (a) System topology. (b) Exemplified equivalent circuit.

Table 5. Critical comparison of typical MIMO WPT systems.

Type	Applicability	Implementation	Objectives	Features
MFF	• Multiple transmitters • Single receiver		• Maximized magnetic field intensity at one specific position [121, 122]	• Linear model • Inductor array for current control [121] • Variable parameters in components • Not suitable for dynamic WPT
MFB	• Multiple transmitters • Multiple receivers		• Maximized output powers for authorized receivers [123-125] • Null steering of output power for unauthorized receivers [119]	• Non-linear model • Simplified control system • Suitable for dynamic WPT
MFE	• Multiple transmitters • Multiple receivers		• Customized output powers for authorized receivers • Null steering of output powers for unauthorized receivers • Suppression of magnetic field intensities at specific positions	• Linear model • Customized output powers • Simplified control system • Flux leakage suppression [59] • Suitable for dynamic WPT

4.3.1. Magnetic Field Focusing

The synthesized MFF technique uses the multi-transmitter current control. It aims to focus the magnetic field to a single position on a one-dimensional line [121] or two-dimensional plane with a relatively high resolution [122]. Besides the general configuration in Fig. 20, another system configuration for MFF is shown in Fig. 21(a), and its potential application is for the RF barcode as shown in Fig. 21(b)

[121]. The system requires multiple separate DC voltage sources to form a single strengthening position of magnetic field intensity (|B|) in the area concerned. With a single objective, the system can reach its maximum output for the targeted position. On the other hand, it is suitable for static applications only, and its dynamic traceability and controllability deserve to be explored further.

4.3.2. Magnetic Field Beamforming

The MFB was originated from the literature [123] and developed from the literature [124]. The system design aims at maximizing the total receiving power for one or multiple objectives in the dynamic operation. For a general MIMO system in Fig. 20, assuming that the number of transmitter coil is n, and the numbers of authorized and unauthorized receivers are p and q, respectively, the commonly used optimization model can be expressed as (P0) [119, 125]:

$$\text{(P0): } \max P_{\text{out}} \tag{2a}$$

$$\text{Subject to } \; P_{\text{in}} \le C \tag{2b}$$

$$P_{\text{rx},\,i} \ge P_{\text{on},\,i}^{\text{th}}, \quad i \in [1,\, p] \tag{2c}$$

$$P_{\text{rx},\,j} \le P_{\text{off},\,j}^{\text{th}}, \quad j \in [1,\, q] \tag{2d}$$

where P_{in} and P_{out} are the total input and output powers of the whole system, respectively; $P_{\text{rx},i}$ is the wireless power received by the i^{th} receiver; and $P_{\text{on},i}^{\text{th}}$ and $P_{\text{off},j}^{\text{th}}$ are the accordant power thresholds for the i^{th} authorized receiver and the j^{th} unauthorized receiver, respectively. Both the objective and the constraint conditions are second-order functions for the model (P0). The optimization objective is to maximize the output power P_{out} for authorized receivers while limiting the input power P_{in} below a given value C. The output power P_{out} can be expressed as:

$$P_{\text{out}} = \frac{1}{2}\boldsymbol{i}_t^H \boldsymbol{C}^H \boldsymbol{C}\boldsymbol{i}_t, \quad \boldsymbol{C} = \sum_{k=1}^{p} \sqrt{R_{L,k}}\left(j\omega \boldsymbol{Z}_r^{-1}\boldsymbol{M}_{tr}\right) \tag{3}$$

where $\boldsymbol{i}_t$ is the transmitter current vector; $R_{L,k}$ is the k^{th} load resistance; $\boldsymbol{M}_{tr}$ is the coupling information matrix between the transmitters and the receivers; and $\boldsymbol{Z}_r$ is the impedance matrix on the receiver sides. Therefore, transmitter current vector is the variable that should be optimized in (P0). For various system topologies, this model easily becomes nonconvex non-deterministic polynomial-hard [126, 127], which requires an extra relaxation procedure.

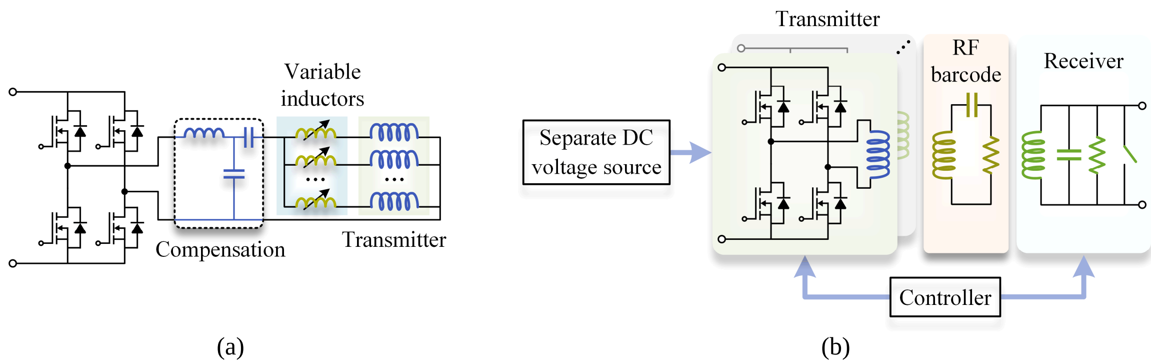


Fig. 21. Typical configurations of MFF system. (a) System topology. (b) Application for RF barcode.

4.3.3. Magnetic Field Editing

A technique of magnetic field editing was developed recently to further adapt to different practical applications [59]. Its system topology is the same as that of MFF or MFB as shown in Fig. 20. The aim is to use a piece-wise optimization process to take place of the single objective model and simplify the computation burden. The desired output power for different receivers can be predetermined at each position concerned. Under different constraint conditions for practical considerations, the optimal ratio of transmitter currents will be calculated to approach the objective value. Finally, the transmitter currents can be adjusted and determined by relevant constants for different output levels. For the flux leakage suppression at m specific positions, one of the most typical optimization models can be expressed as (P1):

$$\text{(P1): } \min \left\| \boldsymbol{v}_p^{\text{th}} - \boldsymbol{v}_p \right\|_2 \tag{4a}$$

$$\text{Subject to } B_i \le B_i^{\text{th}},\ i \in [1, m] \tag{4b}$$

$$\|\boldsymbol{v}_t\|_\infty \le \Gamma \tag{4c}$$

where $\boldsymbol{v}_p$ and $\boldsymbol{v}_p^{\text{th}}$ are the vectors formed by induced voltage and the accordant objective values at each position concerned, respectively; B_i and B_i^{th} are the magnetic flux densities at the i^{th} concerned position and the accordant thresholds, respectively; (4c) constrains that the maximum value of transmitter voltage should be under a certain threshold Γ; and $\|\cdot\|_2$ and $\|\cdot\|_\infty$ are the Euclidean ($\boldsymbol{L}^2$) norm and the infinity norm of vectors, respectively. The optimization objective is to maximize the magnetic flux densities at targeted points while suppressing those at non-targeted points. The induced voltage vector can be expressed as:

$$\boldsymbol{v}_p = \left[\sum_i j\omega M_{ti1} I_{ti} \quad \sum_i j\omega M_{ti2} I_{ti} \quad \cdots \quad \sum_i j\omega M_{tip} I_{ti} \right]^T \tag{5}$$

where M_{tij} is the mutual inductance between the i^{th} transmitter coil and the receiver coil when it is positioned at the j^{th} ($j \in [1, p]$) point, and I_{ti} is the value of the i^{th} transmitter current. Therefore, transmitter current vector is also the variable that should be optimized in (P1). Each function in (P1) can become linear and much easier to be dealt with as compared to the traditional models. Also, both the priority and different power requirements can be incorporated into the objective voltage vector $\boldsymbol{v}_p^{\text{th}}$, which gives the system more flexibility and controllability.

For wireless energy MIMO, the transfer distance equals the diameter of each unit coil in the transmitter array, such as 100 mm, and the transmission efficiency can reach around 80% [59]. Enlarging each unit coil can support a longer transfer distance. By applying the PFM for soft-switching [40], the efficiency can be effectively improved further during magnetic field editing in the MIMO energy system.

5. Wireless Energy Internet

Wireless EI will become the backbone of developing the future power network by integrating the smart grid and the internet while embracing the transportation network and other energy networks [17]. It mainly contains five parts: (1) wireless energy charger, (2) wireless energy exchanger, (3) WER, (4) wireless energy architecture, and (5) wireless energy infrastructure.

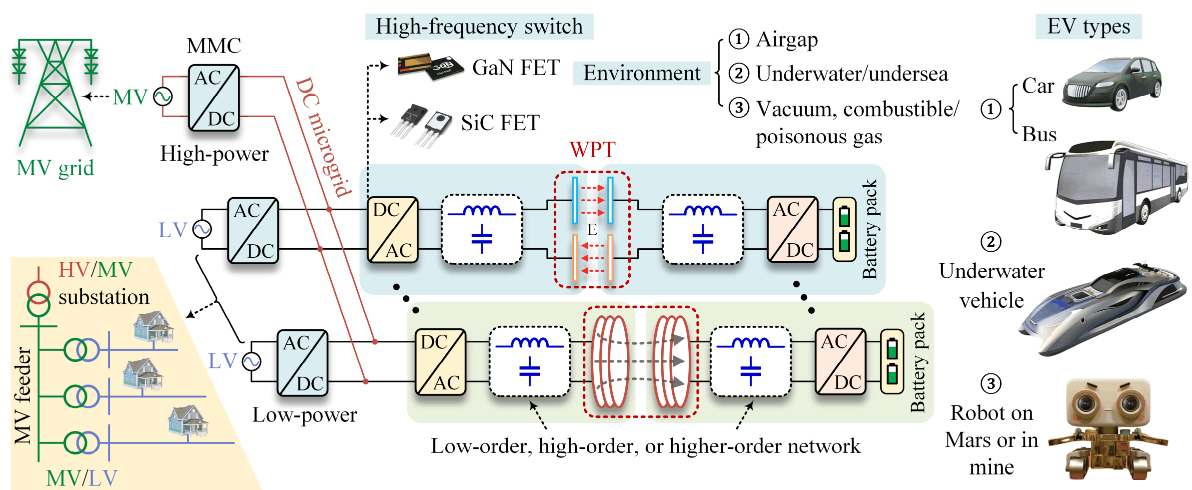


Fig. 22. Wireless charging system using different technologies for various EVs.

5.1. Wireless Energy Charger

Wireless chargers have numerous advantages over wired chargers for battery charging, such as better safety, higher convenience, stronger electrical isolation, and less maintenance [128]. Wireless charging has been actively developed for various applications, in particular for EVs [129], portable electronics, and medical devices. Fig. 22 shows the wireless charging system using different topologies for various EVs [130]. Fig. 23(a) shows the configuration and power flows of a wireless energy charger. The wireless charger mainly contains three parts: the high-frequency converter, coupler, and compensation network [76]. Incorporating with the new charging method of MCC, MHC or STC, the wireless charger can facilitate the battery pack to perform its performance well.

The wide bandgap semiconductor devices, such as SiC and GaN FETs, accelerated the development of wireless chargers for EVs and portable devices [131]. They have the main advantages of higher switching frequency, less switching loss, and higher power density. To realize the goals of high system efficiency (>95%) and high-power capacity (such as 2~50 kW or larger) [132], both the DC/AC and AC/DC converters work within the high-frequency regime, typically 80~90 kHz for EV wireless charging. Besides, the mechanism of magnetic resonant coupling is utilized for approaching these goals, and the WPT can be further divided into three types: the IPT [133], CPT [134], and their hybrid combination. In Fig. 22, the high-power modular multilevel converter (MMC) [135] or the solid-state transformer [131] can be directly connected to the medium voltage (MV) grid, which can be developed for charging a community of EVs [136] at the parking lots or the multistorey charging buildings. Also, the cascaded MMC or the solid-state transformer can promisingly replace the distributed low-power converters connected with a low-voltage (LV) grid.

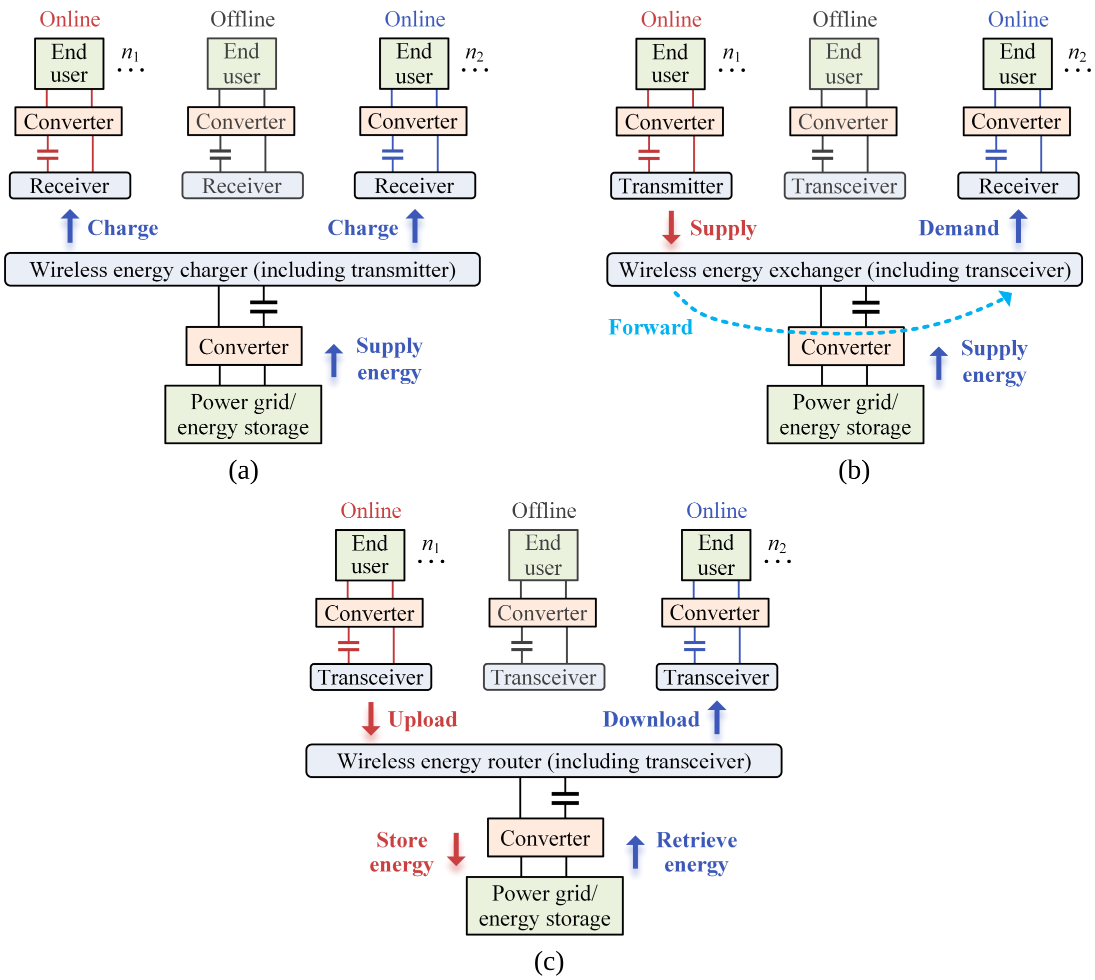


Fig. 23. Wireless energy devices. (a) Wireless energy charger. (b) Wireless energy exchanger. (c) Wireless energy router.

5.2. Wireless Energy Exchanger

Differing from the wireless charger, the wireless energy exchanger can provide a platform supporting the wireless energy exchange among multiple end-users, as shown in Fig. 23(b). It should be noted that the wireless energy exchanger will be not mainly to conduct energy exchange with the power grid or the energy storage system but help forward the wireless energy packets from the energy-supplying users to the energy-demanding users, thus outperforming the wireless energy charger. Its mechanism is similar to the thermal flow of heat exchanger [137, 138]. Accordingly, a wireless power transceiver is deployed in the wireless energy exchanger to support the bidirectional power flow [139]. Furthermore, this wireless energy exchanger can support the peer-to-peer (P2P) wireless charging [45] or P2P wireless energy trading [17], such as for the V2V energy transaction.

5.3. Wireless Energy Router

Besides supporting the bidirectional wireless charging, the WER adds the energy storage system for uploading and downloading the unbalanced wireless energy packets [17, 140], as shown in Fig. 23(c). The energy packets, alike data packets, are units of energy collected into one set for transmission through the WPT network. Data packets are digitalized into data sets for information transmission in communication networks, while energy packets are not digitalized into data sets, but their features, such as frequency or quantity, are encoded by using data sets for transmission, encryption, uploading, downloading and trading. More dimensional energy encryption can be explored, such as position encryption or inductive and capacitive hybrid WPT encryption. The encryption technology of data packets can be borrowed to encrypt the energy packets. The delivery of security keys can use the data encryption technology. Finally, the energy packet security can be comparable to the data packet security. Thanks to the technological development of wide bandgap semiconductor devices, the energy consumption for encryption will lead to insignificant efficiency loss by around 1% or less. However, without applying the energy encryption technology, the efficiency loss can reach up to 50% once energy theft happens, which should be strictly prohibited.

For different scenarios during the wireless energy trading, the WER can mainly perform three functions: absorbing the oversupplying energy packets, compensating for the overdemanding energy packets, and forwarding the self-balancing energy packets [141]. The WER can serve as a utility interface to connect with the renewable energy and other energy networks, and it can help realize the wireless energy routing and scheduling [142, 143] in the wireless EI. Promisingly, the mobile EVs can trade, deposit and withdraw their wireless energy packets on the WERs in a regional league of the traffic EI [17]. Correspondingly, the WER is capable of forwarding, uploading and downloading the wireless energy packets by coordinating between the EVs and the EIs. All these activities can thus coordinate with the power grid and achieve the energy management and distribution in green and smart cities.

5.4. Wireless Energy Architecture

Fig. 24 shows the evolution of wireless energy architectures for EV wireless charging [130, 131]. Figs. 24(a) and 24(b) show the wireless energy architectures sharing the AC bus and the DC bus, respectively, where a low-frequency transformer is inserted between the MV grid and the LV grid. Both the renewable energy and the energy storage systems can be readily integrated into the aforementioned wireless energy architectures that support the V2G operation [144-147]. In Fig. 24(c), another advanced energy architecture actively involves the cascaded MMC as a solid-state transformer to replace the traditional transformer [136, 148]. Wherein, multiple isolated DC/DC converters help the MMC provide the multiple outputs in parallel for EV charging. Hence, a DC microgrid is formed, and it embraces the distributed energy storage systems [149] and clean energy [143]. Wireless energy charger, exchanger and router will serve as the energy interfaces with EIs and smart grids [150, 151]. Thanks to the vehicular energy storage system [152, 153], a community of EVs works as a smart load to coordinate with the MV grid freely [154], termed vehicular C2I.

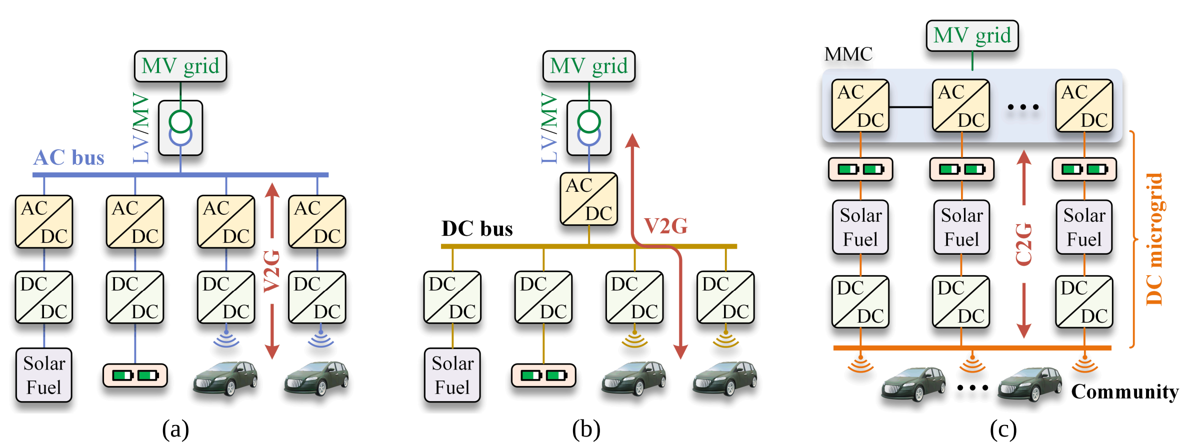


Fig. 24. Wireless energy architectures. (a) AC bus sharing. (b) DC bus sharing. (c) DC microgrid.

5.5. Wireless Energy Infrastructure

In Fig. 25, the smart EI is envisioned by embracing various wireless energy infrastructures including the wireless charging stations [155], multistorey charging buildings, underground piping network [14], wireless EV energy network [18], and traffic EI [17]. Internet of Things (IoT)-based infrastructure will communicate and coordinate all the wireless energy infrastructures [155, 156].

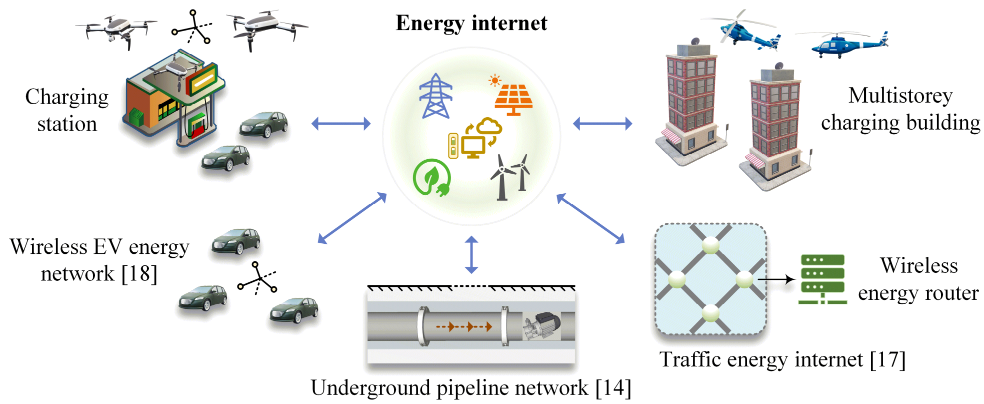


Fig. 25. Typical wireless energy infrastructures.

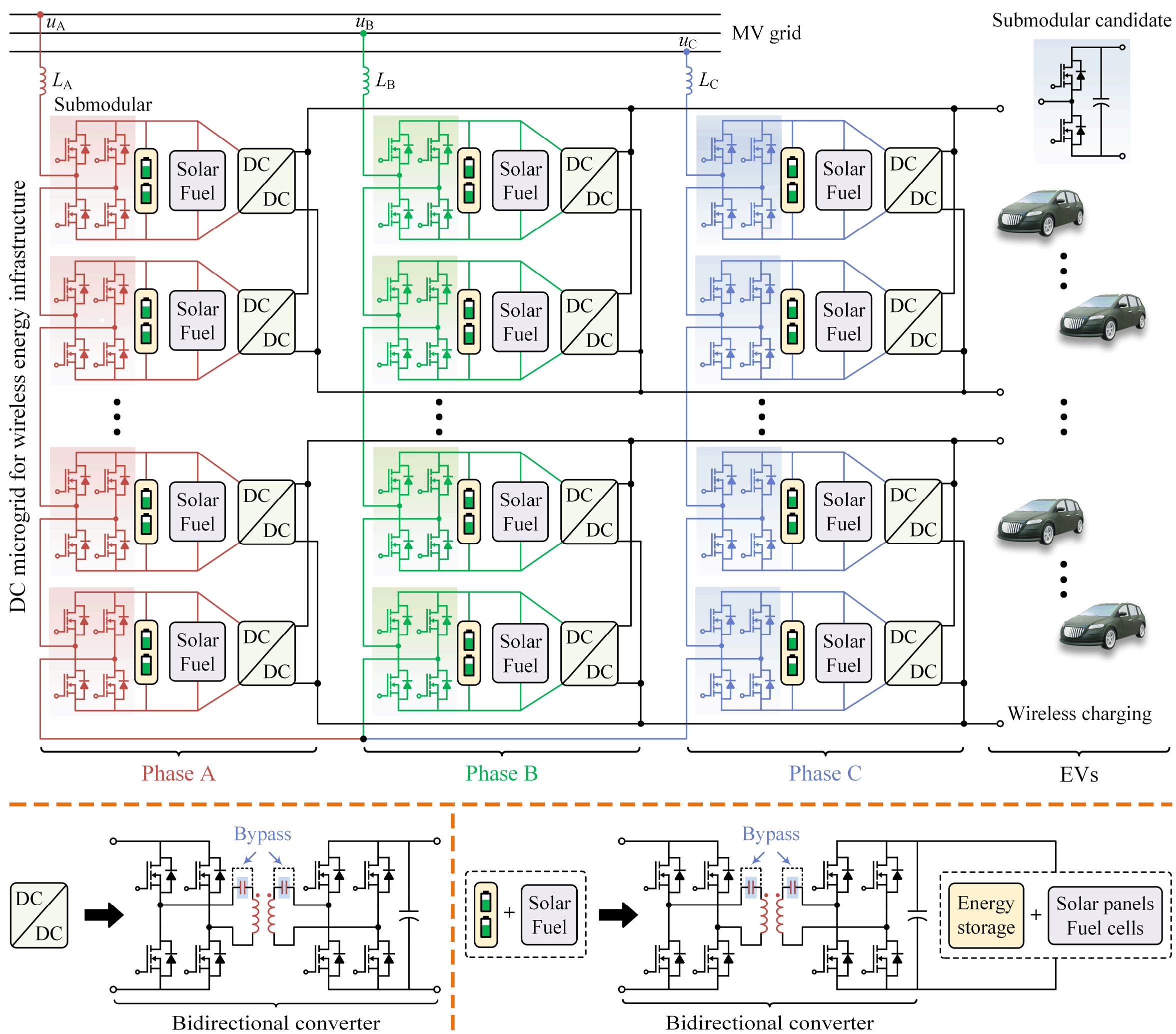


Fig. 26. Implementation of wireless energy infrastructure with bidirectional power conversion.

By intervening in the price of electricity, the charging strategies will be affected in the multistorey charging buildings, and the traffic flow pattern will be managed in the transportation networks electrified with roadway charging for EVs [157-159]. Hence, routing the traffic flow and planning the EV charging can help mitigate congestion in the physical electricity network [160-162]. Also, the application of big data, AI, cloud computing can help make the optimal decision for energy routing and energy scheduling [163]. The traffic EI differs from the wireless EV energy network because the WERs are deployed at the major traffic junctions. Once encountering a terrorist attack, the traffic EI can flexibly detach from the physical power grid to operate independently [17]. In the wireless EV energy network and traffic EI, transportation electrification will bring the advantages of energy and environmental sustainability, thus reducing the carbon footprint and promoting the carbon neutrality [164, 165]. In addition, the wireless piping network can free the use of physical cables and batteries (such as LIBs), which is suitable for developing the urban drainage system and in-pipe robots [166, 167]. Moreover, the magnetic concrete pipelines will further improve the performances of WPT and WDT from the ground transportations to the underground pipeline transportations [168, 169].

Fig. 26 demonstrates the underlying implementation of wireless energy infrastructure, in particular for multistorey charging buildings [130]. Wherein, the cascaded MMC is in charge of bidirectional power conversion between the MV grid and the LV grid, thus enabling the wireless energy infrastructures to embrace the smart EIs. With the deployment of WERs, the wireless energy transceiver in the DC microgrid can support to upload, download and forward the energy packets for routing the energy flows. Besides the services of energy deposit and withdrawal in the EI, each registered EV or vehicular society can earn deposit interest and conduct wireless energy trading to get arbitrage [17].

6. Wireless Energy Trading

With the ever-increasing growth of wireless EIs, wireless energy trading will become one of the most promising development trends in the next decade(s). With the help of wireless energy modulation, the technologies of energy encryption and energy-on-demand can guarantee the security of wireless energy transactions. According to the market size, the wireless energy trading can be classified into three types: (1) P2P energy trading (such as V2V), (2) P2C energy trading (such as V2H, V2C, and V2G), and (3) C2I energy trading (such as community to grid).

6.1. Peer-to-Peer Energy Trading

In modern society, conventional consumers gradually evolve into prosumers. For example, EVs are not only energy consumers but also distributed energy resources owing to the integration of the energy storage system, such as the LIB pack [170]. To incentivize the coordination among plenty of distributed energy resources, P2P energy trading can actively manage the consumption, production and storage of energy in a conceived virtual power plant [171]. Energy trading is welcomed between electronic devices (e.g., mobile phones), EVs, households or even communities that adopt renewables (e.g., photovoltaics) and energy storage (e.g., EVs) [172]. Also, community-to-community energy trading can be treated as a kind of P2P energy trading. Accordingly, energy cost optimization [161] and shortest path preference [173, 174] were actively studied, respectively, to reduce the power loss and improve the energy efficiency. During P2P energy trading, incentivizing coordination can optimize the large-scale demand to increase the network efficiency and the energy security [175]. Fig. 27(a) shows the hierarchy of P2P wireless energy trading, where the V2V energy trading is exemplified based on the WERs [17]. Apart from carrying passengers for a fare, future EVs can trade their wireless energy packets to earn profits. However, the energy density and cycle life of batteries, such as LIBs, may challenge the energy trading speed and transaction frequency among peers.

6.2. Peer-to-Community Energy Trading

In addition to P2P wireless energy trading, the prosumers, with production, consumption and storage capabilities, bring new challenges and opportunities for the energy market [176]. Correspondingly, besides the V2V operation, the V2H and V2G energy networks [177] will support the P2C wireless energy trading. Prosumers can trade their energy packets with peers or the microgrid freely, and the auction mechanisms will help prosumers select optimal buyers in the whole microgrid, thus enabling the autonomous energy trading including the P2P and P2C transactions [178]. Inspiringly, a P2P energy trading platform “Elecbay”

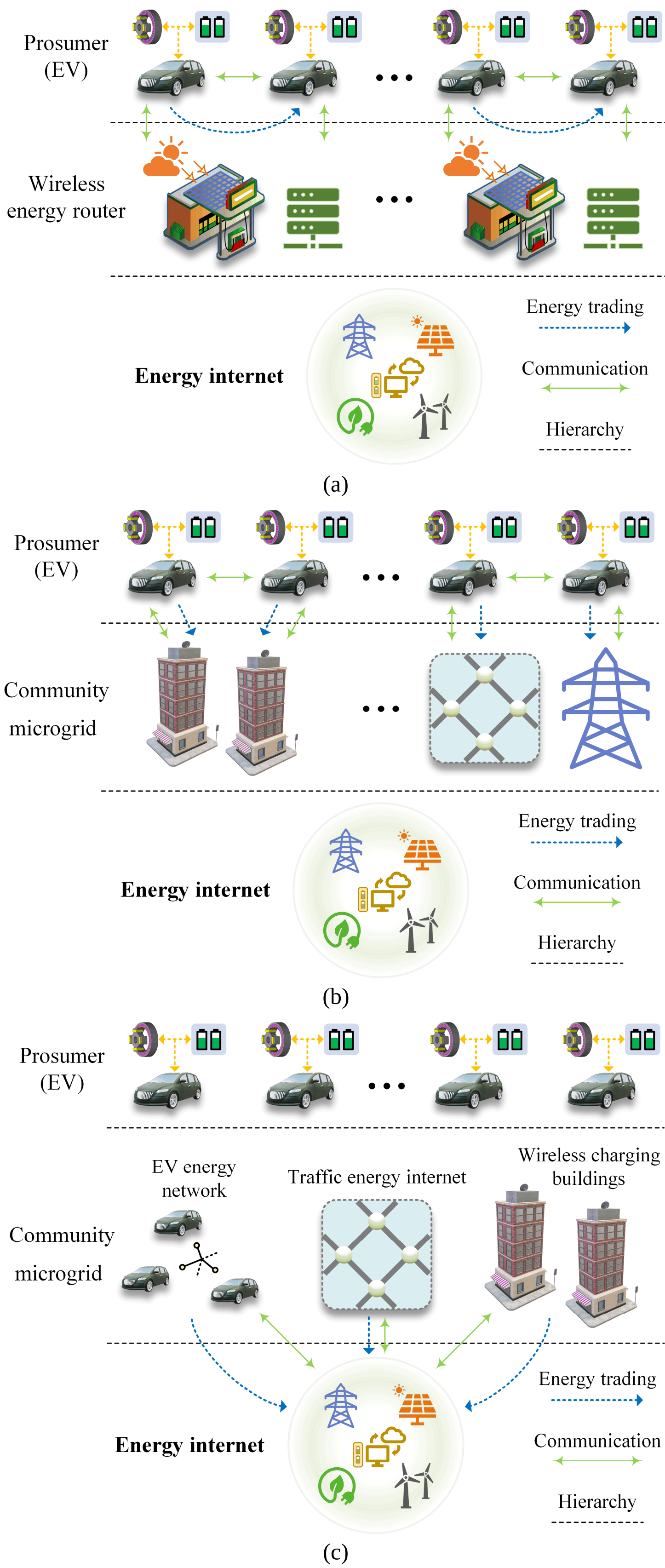


Fig. 27. Wireless energy trading. (a) Peer-to-peer. (b) Peer-to-community. (c) Community-to-internet.

was designed with the use of the game theory [179]. Such a platform is capable of supporting the P2C energy trading between prosumers and microgrids. Moreover, a game-theoretic model was developed and applied to a small community microgrid [180], thus guiding the P2P and P2C energy trading in order. To form an economic and sustainable community, buildings with energy can directly share their energy supplies and demands and offer the related payments within the community [181]. Wherein, distributed prosumers can subscribe to the purchase orders and the energy offers originated from the buildings. Fig. 27(b) shows the hierarchy of P2C wireless energy trading, where the wireless charging buildings, traffic EI and microgrid can perform the P2C energy trading, thus contributing the advanced energy management for a green community.

6.3. Community-to-Internet Energy Trading

On top of the P2P and P2C wireless energy trading, WERs can transact their wireless energy packets with the upstream smart EI. Fig. 27(c) shows the hierarchy of C2I wireless energy trading. Wherein, wireless EV energy networks and traffic EI are deployed with distributed WERs, while wireless charging buildings can be modeled as WERs. All these energy communities can trade their huge energy packets with the smart EI via the smart WPT interfaces. The smart EI integrates the renewable network, electricity network, communication network and various IoTs, and it enables the flexible deployments of P2P, community-to-community and region-to-region energy trading.

In recent years, the hierarchy of C2I energy trading comprises large-scale energy transactions in electricity networks. Accordingly, various technical approaches were reviewed to address the challenges in the large-scale P2P transactions [182], which provide valuable reference significance for treating the C2I trading hierarchy. With the rapid advancement of blockchain technologies, the P2P energy trading mechanism was driven by the blockchain technology that helps address the design problem of a sustainable microgrid [183]. Such blockchain technology can be extended to manage the C2I energy trading behaviors. To ensure the secure energy trading in the industrial IoT, including the microgrids, renewable network and wireless EV energy networks, the consortium blockchain technology was actively considered to form an energy blockchain [184]. Furthermore, it was suggested as a solution to the problem of privacy leakage without restricting any trading functions, thus guaranteeing the privacy-preserving energy trading in the smart EIs [185].

With the ever-increasing technology of information communication and computers, the state-of-the-art technologies of AI and cloud computing will further promote the advancements of future smart WPT, especially for emerging wireless energy markets as well as wireless energy and data sharing. By interfacing more renewables, the smart WPT technologies, in turn, will provide cleaner and safer energy services for the green community and smart city.

7. Conclusions

The smart WPT promotes technological advancement in the industrial, domestic and medical fields. It also brings new opportunities and challenges to our modern technology and human society. This review has thoroughly discussed the key technologies of the following five aspects: (1) Executor of wireless energy modulation; (2) compiler of wireless energy conversion; (3) programmer of wireless energy intellectualization; (4) foreteller of wireless energy internet; and (5) guider of wireless energy trading. Their methodologies, approaches and features are presented in detail. Some open research problems are identified for the guidance of further efforts.

(1) System optimization of WPT shall be targeted at improving the whole-process energy efficiency, rather than improving the peak efficiency at specific power points.
(2) Wireless energy conversion, including wireless charging, wireless lighting, wireless heating and wireless motoring, deserve to be explored further, which can inspire more schemes for practical applications and commercialization. In particular, sensorless wireless chargers and sensorless wireless motors can be developed promisingly.
(3) Biomedical wireless millirobots using wireless motors can be explored for promisingly improving the modality of treatments, such as minimally invasive surgeries, drug delivery or capsule endoscope.
(4) Future wireless power will be endowed with more intelligence and functionality, such as for wireless energy encryption, magnetic field editing and wireless power drive.

(5) Wireless EV energy networks will be established to incubate a new business model of "Uber Energy" for wireless energy trading, which can collaborate with other energy networks, such as renewable energy network and electric power network, thus facilitating multiple network merging.

This article aims to reveal the foresights of smart WPT technologies and envision the concepts of wireless EI and wireless energy trading among peers, communities and internets. With the multi-network integration of information, energies, economics and humanity, the smart WPT will greatly promote wireless data and energy sharing in smart EIs and smart cities.

Author Contributions

Wei Liu and K.T. Chau developed the idea, carried out the analysis, and wrote the whole paper. Xiaoyang Tian, Hui Wang, and Zhichao Hua helped prepare several topics and made important suggestions.

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Conflicts of Interest

The authors declare no conflict of interest.

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