

# 1

## The Era of Wireless Power Transfer

As one of the most epoch-making technologies, the wireless power transfer (WPT) can realize the energy transmission in a cordless way [1, 2], which is obviously changing our traditional usage pattern of the energy, thus promoting the pervasive application of sustainable energies into our daily life. Surprisingly, such a miracle technique is not anything new, yet the original concept can date back more than 100 years ago. The story should begin with a great man, namely Nikola Tesla, as shown in Figure 1.1.

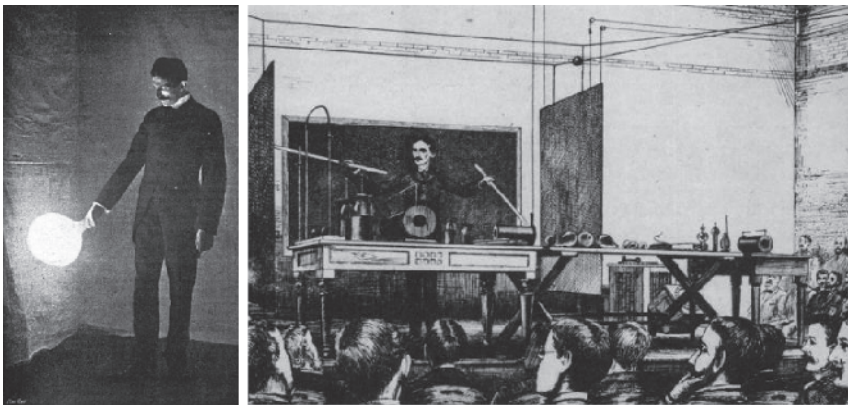
### 1.1 The Father of Wireless Power Transfer – Nikola Tesla

About 130 years ago, the wirelessly transmitting power was successfully demonstrated by Nikola Tesla's series of experiments, where the Geissler tubes and incandescent light bulbs can be lighted from across a stage based on near-field inductive and capacitive coupling, as depicted in Figure 1.2. The key technique of such amazing experiments is to use Tesla coils, which are spark-excited radio-frequency resonant transformers, to generate a high alternating current (AC) voltage [3, 4]. More importantly, Tesla found that the transmission distance could be increased if the LC circuit of receivers can be tuned to resonance with the LC circuit of transmitters [5], namely resonant inductive coupling [4]. Nevertheless, such an imaginative technique failed to proceed with commercialization due to various limitations at that time, such as semiconductor materials, power electronic technologies, and manufacturing.

Tesla's attempting efforts on WPT technologies have never stopped since the beginning of this story. Then, his focus moved to a wireless power distribution system, which can wirelessly deliver the power directly to everywhere in the world. Borrowing from the idea of Mahlon Loomis [3], he developed a demonstrating system composed of balloons to suspend transmitting and receiving electrodes in



**Figure 1.1** Nikola Tesla [3]. Source: Wikimedia Commons.



**Figure 1.2** Demonstrations of wireless lighting by Tesla. Source: Ref. [2] Nikola Tesla/Wikimedia Commons/Public Domain.

**Figure 1.3** Tesla's unsuccessful Wardencllyffe power station. Source: Ref. [2] Nikola Tesla/Wikimedia Commons/Public Domain.



the air above 9100-m altitude, because he believed that the low-pressure air at high altitude would allow higher voltage for long-distance power transmission. In 1899, Tesla build up a test facility at high altitude in Colorado Springs to further study the conductive characteristics of low-pressure air [3]. It is this famous experiment that led Tesla to incorrectly conclude that the entire Earth can be utilized to conduct electrical energy [3]. In addition, the potential of the Earth can be oscillated by driving AC pulses into the Earth at its resonant frequency using a grounded Tesla coil. In such a way, he believed that the AC power can be picked up at everywhere around the world using a similar capacitive antenna tuned to resonance with the Earth [3, 6].

Then, Tesla boldly proposed a “World Wireless System” to deliver both the information and the power around the world [3]. In 1901, a large high-voltage wireless power station, namely Wardencllyffe Tower, was built at Shoreham in New York, as depicted in Figure 1.3. Unfortunately, this project had to be halt due to dried-up investment by the year 1904. Despite all this, Nikola Tesla really redefined the energy transmission and opened up a brand-new research field, who is well deserved to be called the *Father of Wireless Power Transfer* [7].

## 1.2 Wireless Power Transfer

As one of the revolutionary technologies, WPT can realize the transmission of electric energy from the transmitting end to the desired pickup device in a contactless

manner. From the perspective of the transmission distance, the WPT can be mainly divided to near-field transmission and far-field transmission. On the one hand, the near-field power transfer is based on the electromagnetic field coupling theory, including the inductive and capacitive coupling mechanisms. On the other hand, the far-field power transfer can be realized by means of acoustic, optical, and microwave methods, which are applied in low-power sensor networks and military fields. The different wireless power technologies are shown in Table 1.1.

### 1.2.1 Acoustic

The acoustic power transfer can achieve the wireless power transmission in the form of acoustic waves or mechanical vibrations. As shown in Figure 1.4, the system of the acoustic power transfer mainly includes four constituent units, namely the primary AC power supply, the primary and pickup sensors that realize the conversion of electrical energy and mechanical acoustic energy, and the energy pickup side.

The far-field power transfer can be realized in the acoustic mechanism with the help of the ultrasonic frequency of vibration. Meanwhile, a variety of transmission media, including living tissue, metal materials, and air, are suitable for the acoustic mechanisms. Nevertheless, the acoustic power transfer faces the following three challenges. Firstly, the principle of spatial resonance puts forward special requirements for the placement position of the pickup coil, which limits the application scenario of this technology. Secondly, the technology lacks complete and clear theoretical analysis, which hinders the further development and wide application of the technology. Finally, the design of sensor is an important part of this technology which needs to comprehensively consider the power, efficiency of the system, and the impact of reflections [8].

### 1.2.2 Optical

As shown in Figure 1.5, the optical WPT uses the laser as the medium to transmit energy to the pickup coil. This technology is mainly used in military or aerospace fields that require long-distance energy transmission. Compared with other energy transmission mechanisms, this technology has the following characteristics: the realization of the ultralong-distance transmission, the realization of the centralized and directional energy transmission, and zero interference to radio-frequency applications. Meanwhile, the optical WPT faces the challenges including the low conversion efficiency between light and electricity and the danger of laser radiation. Since the twenty-first century, optical WPT has also been used in industrial consumer electronics or low-power sensors [9].

**Table 1.1** Different wireless power technologies.

Technology	Range	Directivity	Frequency	Antenna devices	Current and/or possible future applications
Inductive coupling	Short	Low	Hz to MHz	Wire coils	Electric tooth brush and razor battery charging, induction stovetops, and industrial heaters
Resonant inductive coupling	Mid	Low	kHz to GHz	Tuned wire coils and lumped element resonators	Charging portable devices (Qi), biomedical implants, electric vehicles, powering buses, trains, MAGLEV, Radio frequency identification (RFID), and smartcards
Capacitive coupling	Short	Low	kHz to GHz	Metal plate electrodes	Charging portable devices, power routing in large-scale integrated circuits, smartcards, and biomedical implants
Magneto-dynamic coupling	Short	N.A. (Not applicable)	Hz	Rotating magnets	Charging electric vehicles and biomedical implants
Microwaves	Long	High	GHz	Parabolic dishes, phased arrays, and rectennas	Solar power satellite, powering drone aircraft, and charging wireless devices
Light waves	Long	High	$\geq$ THz	Lasers, photocells, and lenses	Charging portable devices, powering drone aircraft, and powering space elevator climbers

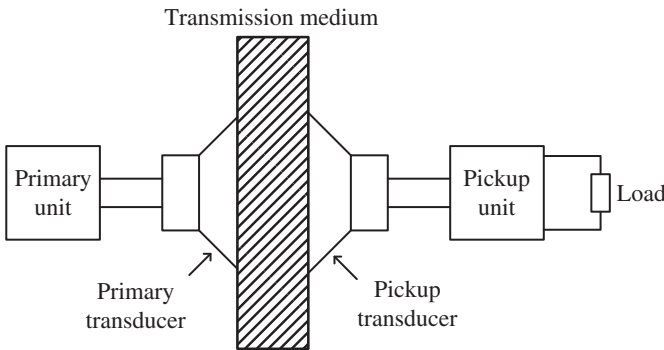


Figure 1.4 Acoustic wireless power transfer.

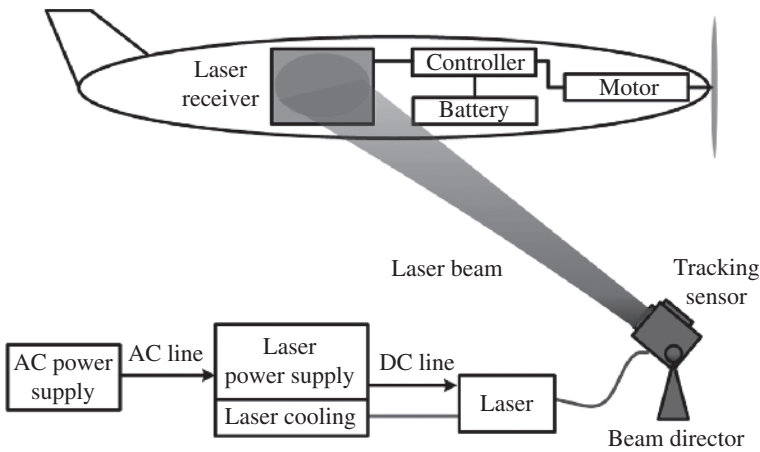
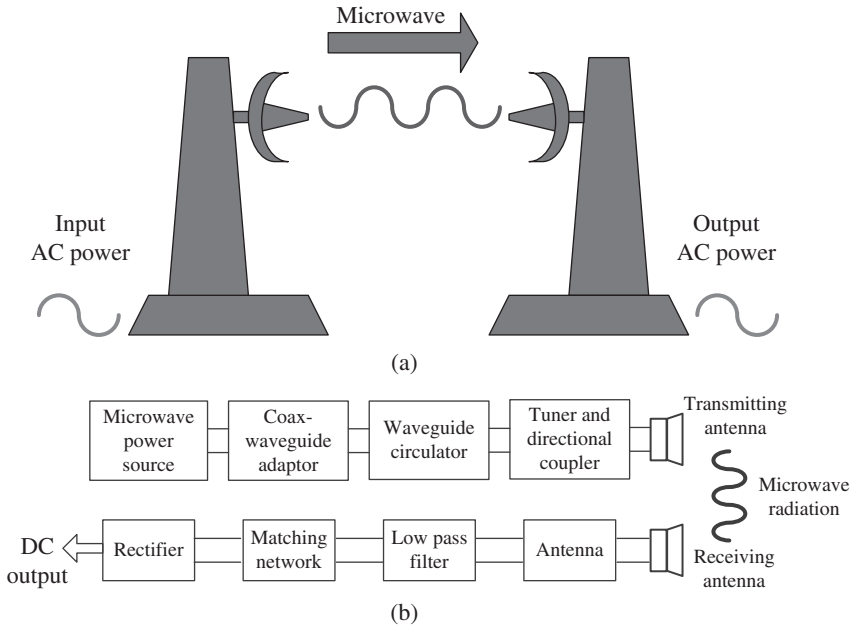


Figure 1.5 Optical wireless power transfer.

### 1.2.3 Microwave

Microwave power transfer technology is a typical far-field wireless power transmission mechanism, which is applied in the low-power sensor networks, space, and military fields. The principle and components of the microwave power transfer system are depicted in Figure 1.6. At the transmitting part, the microwave is generated by the microwave generator and transmitted through the coax-waveguide-adapted and waveguide circulator, which reduces the external radiation caused by microwave. Then, the tuner and directional coupler device are used to realize the separation of radiation signals according to different propagation directions, ensuring the propagation of radiation in the air. In the pickup part, the microwave radiation is received through the receiving antenna and then

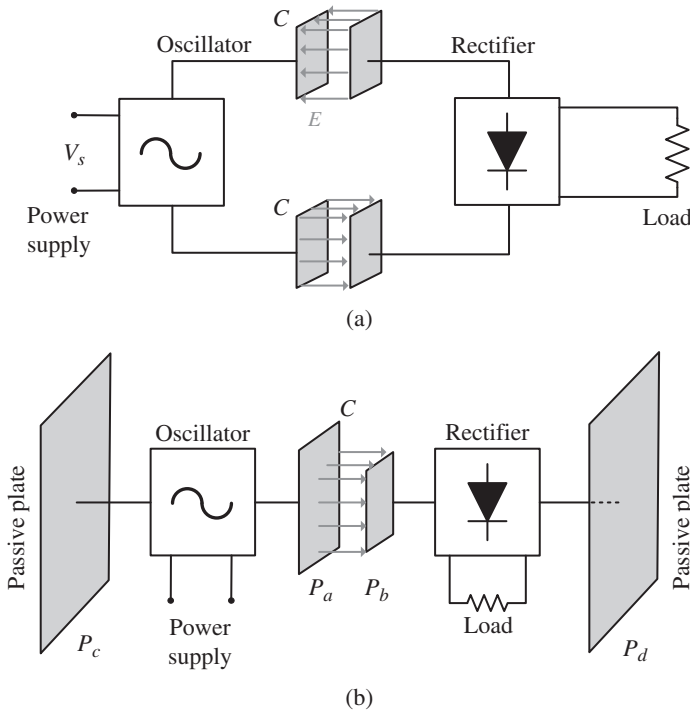


**Figure 1.6** Microwave wireless power transfer: (a) schematic; (b) block diagram of working principle.

converted into DC power through the low-pass filter, matching network, and rectifier [10]. To obtain the best energy conversion efficiency in the wide-range input power levels, a novel rectifier antenna architecture was proposed in the microwave WPT system [11].

#### 1.2.4 Capacitive

The capacitive WPT system mainly consists of the transmitting and receiving electrodes, where the transmitting plate voltage generates an induced AC electromotive force on the receiving plate through electrostatic induction. In this technology, the transmitting power is related to the switching frequency of the system and the capacitance between the plates. According to the number of plates, the capacitive WPT can be divided into unipolar and bipolar systems. As shown in Figure 1.7a, the bipolar system includes two sets of transmitting and pickup plates. Different transmitting plates have  $180^\circ$  voltage phase difference, and AC potentials with opposite phase are induced at the pickup plates to realize wireless power transmission in the bipolar method. In addition, as depicted in Figure 1.7b, the unipolar system can achieve the energy transmission with a set of plates, where the passive plates form the return path at the same time [12].

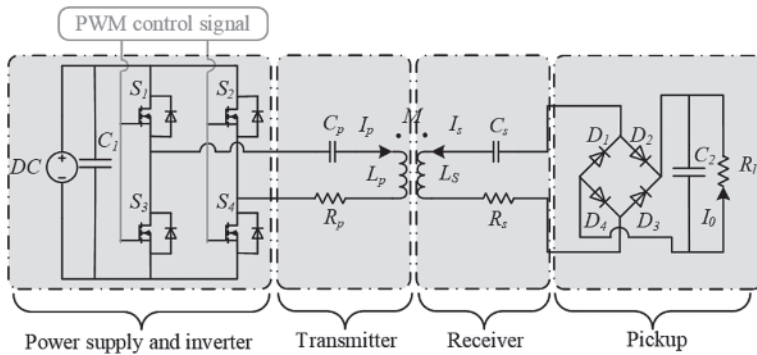


**Figure 1.7** Capacitive wireless power transfer: (a) Bipolar; (b) Unipolar.

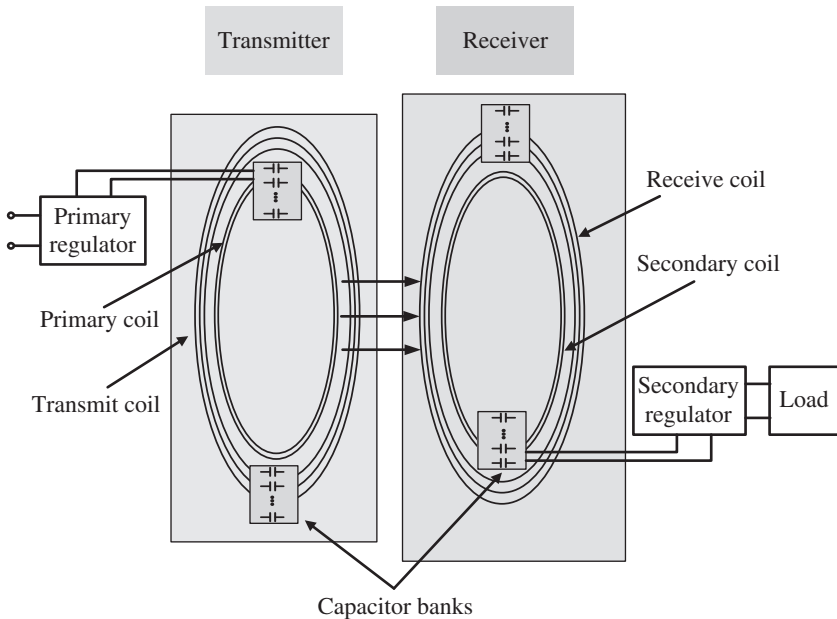
Compared with other energy transmission mechanisms, this technology reduces the need for alignment between the transmitter and the pickup coils and provides a closed energy field to reduce the external interferences. Nevertheless, since the high voltage on the electrode plate will lead to the generation of harmful gases, the technology can only be applied to some low-power wireless charging scenarios.

### 1.2.5 Inductive

As depicted in Figure 1.8, the common inductive WPT system is composed of the primary and secondary parts. In the primary part, the high-frequency AC is generated by DC power supply and inverter. Then, based on the electromagnetic induction mechanism, the high-frequency current is wirelessly transmitted from the primary coil to the pickup coil. In fact, the induced power transfer system is similar to the transformer system with weak coupling strength. Besides, the magnetic materials such as the ferrite can enhance the coupling strength between the primary and pickup coils [13].



**Figure 1.8** Inductive power transfer.



**Figure 1.9** MRC-based wireless power transfer.

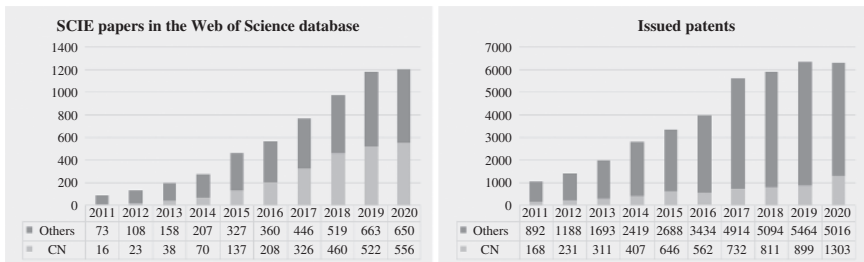
Moreover, the magnetic resonant coupling (MRC) mechanism can help to increase the transmission performance of inductive power transmission, which has broad application prospects in medium-distance and low-power applications. In Ref. [14], the effectiveness of MRC mechanism was proved by the WPT experiment with a transmission distance of 2 m and a power of 60 W. Figure 1.9 describes the basic components of four-coil MRC-based WPT system, including

high-frequency AC power supply, compensation network of the transmitting and receiving coils, and the load side. Different from the inductive power transfer, the MRC-based system must use the capacitance compensation network to ensure that the system works in a resonant state.

Based on the MRC mechanism, the energy can be simultaneously transferred to different pickups in a wireless way [15]. Besides, to maximize the transmission efficiency and distance of the system, the theoretical analysis was proposed based on the equivalent circuit and Neumann formula [16]. Also, the coils with noncoaxial and circular structures were proposed to achieve the domino-resonator WPT system [17]. Furthermore, to avoid the adverse effects of system detuning, an adaptive impedance matching system was implemented by matching the primary and secondary compensation networks to the resonant frequency of the system [18].

As a typical application scenario of inductive power transfer technologies, electric vehicle (EV) wireless charging system has obtained abundant achievements. For instance, to realize the online charging of EVs, an inductive power transfer system was proposed to provide energy for EVs on the whole road [19]. Besides, a bidirectional interface of inductive power transmission was designed to achieve the simultaneous charging and discharging of multiple EVs [20]. Also, to ensure the safe operation of wireless charging system, a load detection model was proposed to monitor the load state of the inductive power transfer system in real time [21]. In addition, the theoretical model of the mutual coupling effect between inductors was introduced to predict the mutual inductance [22].

In fact, due to the development of inductive WPT technology, wireless charging has attracted a lot of attention from academia and business. Figure 1.10 shows the statistics of the published SCIE papers and issued patents about inductive WPT from 2011 to 2020. Besides, many world-famous companies have been engaged in the application and promotion of this technology, such as BMW, Audi, Tesla, Apple, and Huawei, among others. Hence, to standardize the application of the inductive WPT technology, a number of organizations (International Telecommunication Union, SAE International, and Wireless Power Consortium, among others) have issued relevant standards as shown in Table 1.2.



**Figure 1.10** Statistics of studies on IPT: the numbers of SCIE papers from 2011 to 2020 and patents from 2011 to 2020. CN: China

**Table 1.2** Different standard of WPT.

Standard	Title (Content)	Application
Recommendation ITU-R SM.2110	Guidance for the use of frequency ranges for operation of non-beam wireless power transmission for electric vehicle	EV
Report ITU-R SM.2303-2	Wireless power transmission using technologies other than radio frequency beam	All
Recommendation ITU-R SM.2110	Frequency ranges for operation of non-beam Wireless Power Transmission systems	All
IEC61980-1	Electric vehicle wireless power transfer (WPT) systems - Part 1: General requirements	EV
IEC61980-2	Electric vehicle wireless power transfer (WPT) systems - Part 2: Specific requirements for communication between electric road vehicle (EV) and infrastructure	EV
IEC61980-3	Electric vehicle wireless power transfer (WPT) systems - Part 3: Specific requirements for the magnetic field wireless power transfer systems	EV
ISO 19363:2017	Electrically propelled road vehicles? Magnetic field wireless power transfer? Safety and interoperability requirements	EV
ISO 19363:2020	Electrically propelled road vehicles? Magnetic field wireless power transfer? Safety and interoperability requirements	EV
SAE J2954	Wireless Power Transfer for Light-Duty Plug-in/Electric Vehicles and Alignment Methodology	EV
SAE J2847/6	Communication for Wireless Power Transfer Between Light-Duty Plug-in Electric Vehicles and Wireless EV Charging Stations	EV
Qi standard	The world's de facto wireless charging standard for providing 5-15 watts of power to small personal electronics	Phone

### 1.3 About This Book

As mentioned in the preface, this book is trying to introduce working mechanisms, summarize recent research works, and discuss about classic applications of WPT technologies, especially during the past 20 years. It is expected to provide a big picture of WPT technologies for academic researchers, industrial engineers, postgraduate students, and readers who are interested in this research topic. Figure 1.11 shows the organization and the relationship among basic concepts, key technique,

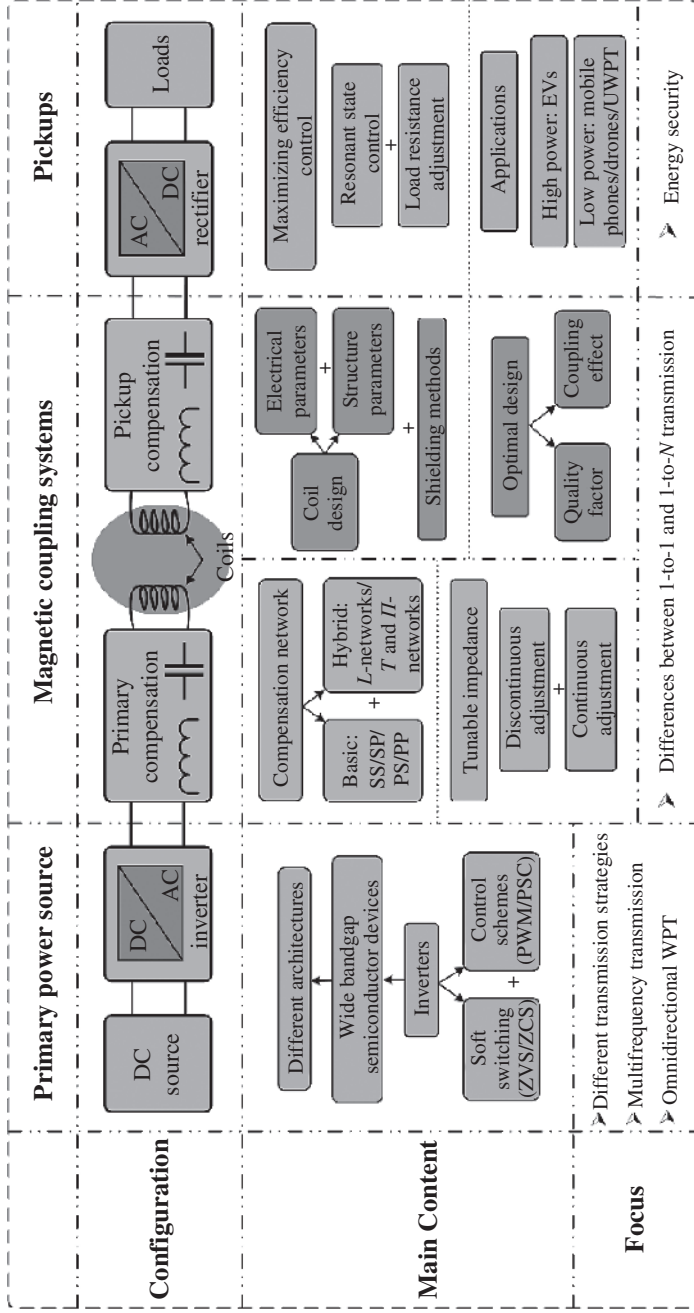
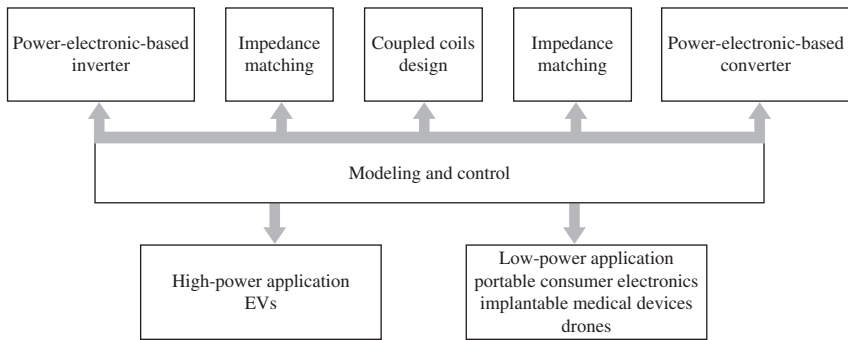


Figure 1.11 Organization of key concepts in this book.



**Figure 1.12** Structure of this book.

and main contents of this book, which is utilized to help readers understand WPT technologies more readily, more intuitively, and more in-depth. As depicted in Figure 1.12, this book covers the multidisciplinary aspects and is organized into the following four parts as:

- Part I presents an introduction and addresses the differences between 1-to-1 and 1-to- $N$  transmission. It consists of Chapters 1 and 2, which introduce the basic theory of inductive power transmission and conclude the system analysis.
- Part II focuses on the design and optimization of coupled coils and power circuits. It comprises two chapters, Chapters 3 and 4, respectively, which discuss the design consideration for coupled coils, coil topology, impedance matching compensation, and DC/AC inverters.
- Part III is the core section of this book, namely the control scheme for WPT. It contains four chapters, Chapters 5–8, in which the maximum efficiency/power control, excitation modulation as well as power allocation for multiple-pickup WPT, energy-encryption-based security consideration control, and omnidirectional vector control are elaborated.
- Part IV unveils promising applications adopting the WPT technique. It includes Chapters 9 and 10, which emphasize EVs, portable consumer electronics, implantable medical devices, drones, and underwater devices.

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