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Wireless Power Transfer

Colin Sokol Kuka

Abstract

In the recent years, the wireless power transfer technique has attracted a lot of attention in research. As a result, it is becoming an increasingly popular technology in consumer electronic devices and electric vehicles. However, there are other methods in which energy could be transmitted, and they could be further classified according to their working ranges, namely the near-field and the far-field transmission. In this chapter, an overview on the principles of different types of wireless power transmission is described. Then, the investigation of the receiver block is discussed through studying the features of rectifier technologies. Later, the book continues to describe the Rectenna system (rectifying antenna) adopted to the Internet of Things (IoT) wireless charge in remote locations.

Keywords: wireless power transfer, near-field transmission, far-field transmission, receiver, rectifier typologies, rectenna system

1. Introduction

Deliver long-range power over great distances is very interesting in the future. For this reason, the Wireless Power transfer (WPT) is a versatile modern technique that can be used by a range of electrical devices. Batteries play an important role in the mobility but have a high initial cost and a short life. For example, the first application of quick wireless charging has been applied in vehicles for public transportation in the traditional bus stations [1]. This form of application has such a small distance between stations and a short waiting period that it has been readily embraced by the WPT for electrical charging. Furthermore, research into EV wireless charging while driving or parking is really appealing and is helping to grow the industry [2]. Another case in point is the spread of so-called commercial electronics. This sector has already seen commercial successes of these WPT systems, particularly for smart-phone chargers, due to the problem of limited battery time and the large use [3]. Although it is difficult to realise those applications because the power must penetrate a thick material like the skin, the benefits of using a WPT device are definitely clear in implantable equipment for health care [4]. Wireless power distribution removes the need for percutaneous cables or surgeries to replace batteries, which may be uncomfortable and infection-prone. This results in a reduced size and lighter weight, or the removal of an energy storage feature that provides patient comfort. In both of these implementations, the propagation distance is critical to the application's reliability.

2. The near-field transmission

An electric power is transmitted from a source such as a generator or a battery to a load if an electric potential differential is applied over a conductor. The use of cables and wires to link the source to a load is the preferred method to allow the electrons flow. However, electronic devices are getting smaller and more compact as technology progresses. Obtaining energy from a cable attached to a power outlet can no longer be a viable option. Mobile devices that involve a smart power supply management are being built and implemented. As a result, a wired connections restrict their mobility and, in some situations, may not be a secure choice if they are damaged.

Electrical energy can be converted into other types of energy that can be transmitted through a particular medium without the use of conductive wires. The use of radio waves to transmit information, such as sound, video and data is a clear example of transmitting energy wirelessly. In a radio station, a voltage signal reflecting the information is produced and then converted into an electromagnetic energy pulse, which is broadcast into the atmosphere, where it spreads in all directions. An antenna detects the electromagnetic energy signal at a lower energy frequency. This signal is then converted back into an electrical voltage signal from which the information is derived.

Depending on the distance between transmitter and receiver, the power can also be converted in energy and then transmitted. Electromagnetic waves are generated in the surrounding media by any electromagnetic field source (point particle, dipole, antenna, or coil). The electromagnetic waves are distinguished by the properties of the fields and how these are associated with the medium in which they are travelling. These fields are normally divided into two types: the near-field and far-field (shown in **Figure 1**), based on their distance from the source and, more specifically, the characteristics of the dominant waves in this area.

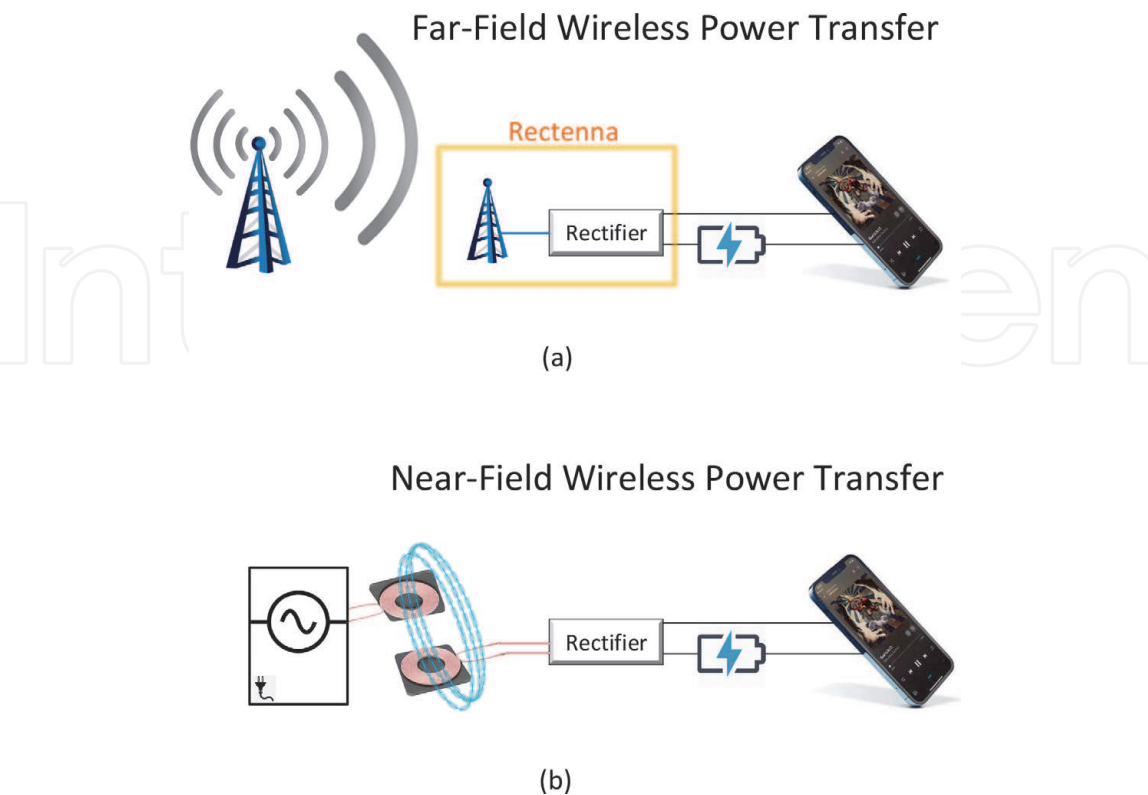


Figure 1.
Representation of wireless power transmission in (a) far field where is highlighted the rectenna, and (b) near field.

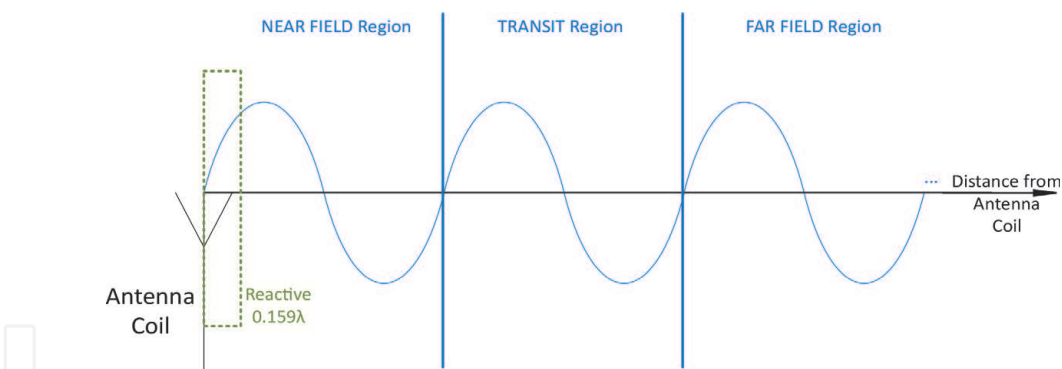


Figure 2.
 Region partition depending from the wavelength λ .

In addition to the near-field, it can be further subdivided into the reactive (non-radiative) near-field and the radiative. The wavelength of the field source is normally used to define these limits as shown in **Figure 2**. As a consequence, an electromagnetic (EM) wave's wavelength, which is proportional to its energy, defines how it interacts with its surroundings. Its limits depends on the wavelength λ [5]. The boundary of the Radiative region is about 1 wavelength, and up to 2λ where a transition region take place. Over than 2λ distance from the transmitter, the far field area starts.

The reactive (non-radiative) region is on the very short range of $\lambda/2\pi$ and it is based on the capacitive or the mutual inductance effect of the antenna. The are used two term to indicate the distance of the transmission: short-range and mid-range. The short-range refers to a transmission wavelength that is less than the transmitter's geometry. The mid-range describes a condition in which the transmission gap is at least two to three times the size of the equipment involved in the power transfer [6].

2.1 Capacitive power transfer

The first methods of electromagnetic coupling were discovered by Tesla in the 1900s [7], by capacitive coupling, which is possible to use the electric field for power transfer in the near-field. However, there was a high voltage present between the transmitter and receiver, which could result in electric shock. The main reason is that the experiment was based on the electric arc. The two electrodes on the capacitor are the transmitter and the receiver of the power transfer system with the air being the dielectric. During each voltage pulse, the output voltage rises to the point where the air around the high voltage terminal ionises, causing corona, brush discharges, and streamer arcs to emerge from the terminal, as shown in the **Figure 3**. This event occurs only when the electric field strength surpasses the air's dielectric strength, which is around $30kV$ per centimetre. Because the electric field is strongest at sharp points and edges on the high voltage terminal, the air discharges begin there [8]. An electric arc discharges by visible light emission, high current density, and high temperature. The voltage on the high voltage terminal cannot rise above the air breakdown voltage because extra electric charge injected into the terminal from the secondary winding simply escapes into the air. Air breakdown limits the output voltage of open-air Tesla coils to a few million volts, but coils immersed in pressurised tanks of insulating oil can attain greater voltages [9, 10].

The CPT is based on this functionality, where two parallel plates (a capacitor) are on a very small distance apart because of safety issues of the above mentioned electric arc. The transmitter is attached to the first plate on each capacitor, and the

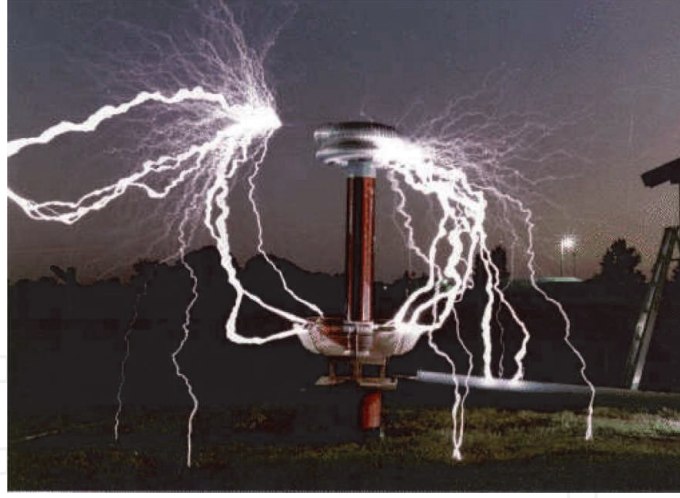


Figure 3.
Recent demonstration of the Tesla experiment in Ref. [8].

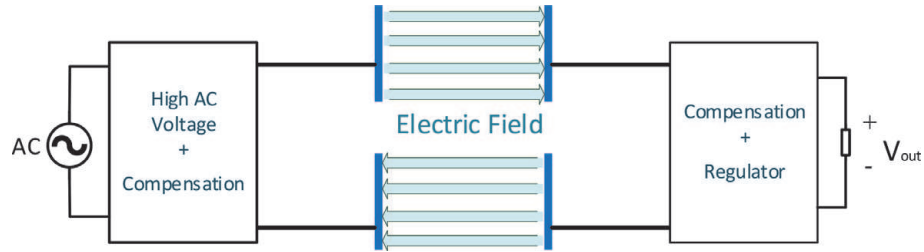


Figure 4.
Principle of the capacitive power transfer (CPT).

receiver is connected to the second plates, as shown in **Figure 4**. Air is the dielectric forming a capacitor of:

$$C_T = \epsilon_R \cdot \epsilon_0 \frac{d}{A} \quad (1)$$

where d is the distance and A is the area of the capacitive plate in the transmitter and in the receiver. This value depends on the dielectric material between the plates, distance, and plate area. Therefore, this value is limited because the permittivity constant ϵ_0 of air is as small as $8.85 \cdot 10^{-12} \text{ F/m}$.

This design can be expanded by adding two connected capacitor plates in both sides (transmitter and receiver) with an electric field between them, as shown in **Figure 4**. The created electric field causes an alternating current to pass in the receiver plates. Thus, power is being sent through the secondary plates of the receiver. The capacitive area is designed after the application, where plates can take on multiple shapes, for example, rectangular, disc, or cone, or specific architecture such as a matrix [10].

The amount of power transmitted (power loss on the components is neglected) through the capacitor electric field is thus approximately calculated:

$$P_R \propto \frac{1}{2} \cdot f \cdot C_T \cdot V_T^2 \quad (2)$$

where V_T is the magnitude of AC voltage in the transmitting capacitor C_T and f is its frequency. It is important to notice that V_T , f and C_T shall be as large as possible in order to deliver more power to the receiver. However, the larger the V_T and f are made, the more switching losses will occur in the electronics circuit. One

of the biggest disadvantages of the CPT has is a poor coupling capacitance C_T and the safety concerns regarding the V_T where in nearly all the applications has a huge value.

2.2 Inductive power transfer

The use of a magnetic field for power transfer has the safety benefit of not using high voltages and not interacting with most biological material. As a result, the magnetic field is used in the majority of modern near-field WPT studies and has a vast range of applications. A non-radiative magnetic field is produced by passing an alternating current (AC) through a coil known as the transmitter, as shown in **Figure 5**. When a load circuit is in vicinity to the reactive area, an electromotive force (EMF) is produced in a second coil, known as receiver. In this way, the electrical power is passed from the transmitter's coil to the receiver's coil. There is a mutual inductance between between the transmitting and receiving coils. This inductance is one of the most significant parameters that affects the power transmitted in inductively coupled wireless power transfer systems.

The mutual inductance M between two coils, Tx and Rx, is shown in **Figure 5**, where alternating current is guided inside coil, Tx, and induced current appears in the coupled coil, Rx. The current flowing in L_T or the transmitter coil sets up a magnetic field, which passes through the receiver coil L_R giving us mutual inductance. When the inductances of the two coils are the same and equal, L_T is equal to L_R , the mutual inductance that exists between the two coils will equal the value of one single coil (as the square root of two equal values is the same as one single value) as shown:

$$M = k\sqrt{L_T L_R} = kL \tag{3}$$

where k is the coupling coefficient expressed as a fractional number between 0 and 1, where 0 indicates zero or no inductive coupling, and 1 indicating full or maximum inductive coupling. One coil induces a voltage in an adjacent coil; therefore, the transmitter L_T induces a voltage v_R^{in} in the receiver, and viceversa.

$$\begin{cases} v_R^{in} = L_R \frac{dI_R}{dt} + M \frac{dI_T}{dt} \\ v_T^{in} = L_T \frac{dI_T}{dt} + M \frac{dI_R}{dt} \end{cases} \tag{4}$$

The amount of power transmitted (power loss on the components has been neglected) through the magnetic field is thus approximately calculated:

$$P_R \propto \frac{1}{2} \cdot f \cdot M \cdot I_T^2 \tag{5}$$

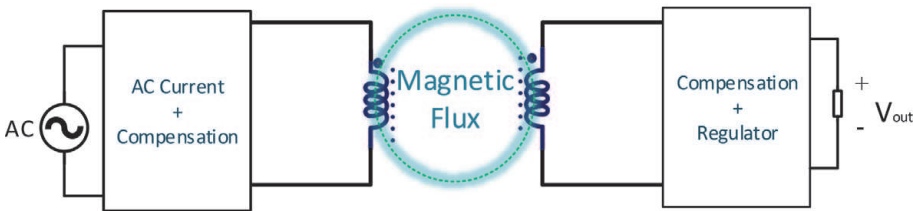


Figure 5.
Principle of the inductive power transfer (IPT).

where I_T is the magnitude of AC current in the transmitting coil L_T and f is its frequency. It could be noticed from this equation that I_T, f and M shall be as large as possible in order to deliver more power to the receiver. However, the larger the I_T and f are, the more switching losses will occur in a power electronics circuit. The current I_T alone will increase the conducting loss on the transmitting coils. Optimising the mutual inductance M is the most efficient option.

Research studies into the inductive power transfer in IPT has been focused on increasing the yield. Performance and reliability are sure to be improved as new designs, components, such as core, coil shapes and configurations, and ways of handling conductivity, are further researched [11–13]. Finite element analysis (FEA) is a computerised method to predicting how the magnetic field is distributed in the air and how coils react to real-world forces, heat and other physical effects. In **Figure 6** it is shown the simulation of WPT system by using ANSYS Electronic v14, where it can be seen the diffusion (**Figure 6a**) and the flux lines (**Figure 6b**) of the magnetic field.

2.2.1 Resonance technique

A largely adopted technique in the near-field magnetic coupling is the resonance which has largely extended the potential of the near-field WPT. A capacitor is connected to the coils to form the LC resonant tank. Therefore, an impedance transformation network is made by the resonant tank at the oscillation frequency f_0 , such that the source VA is minimised and the power transferred to the load is

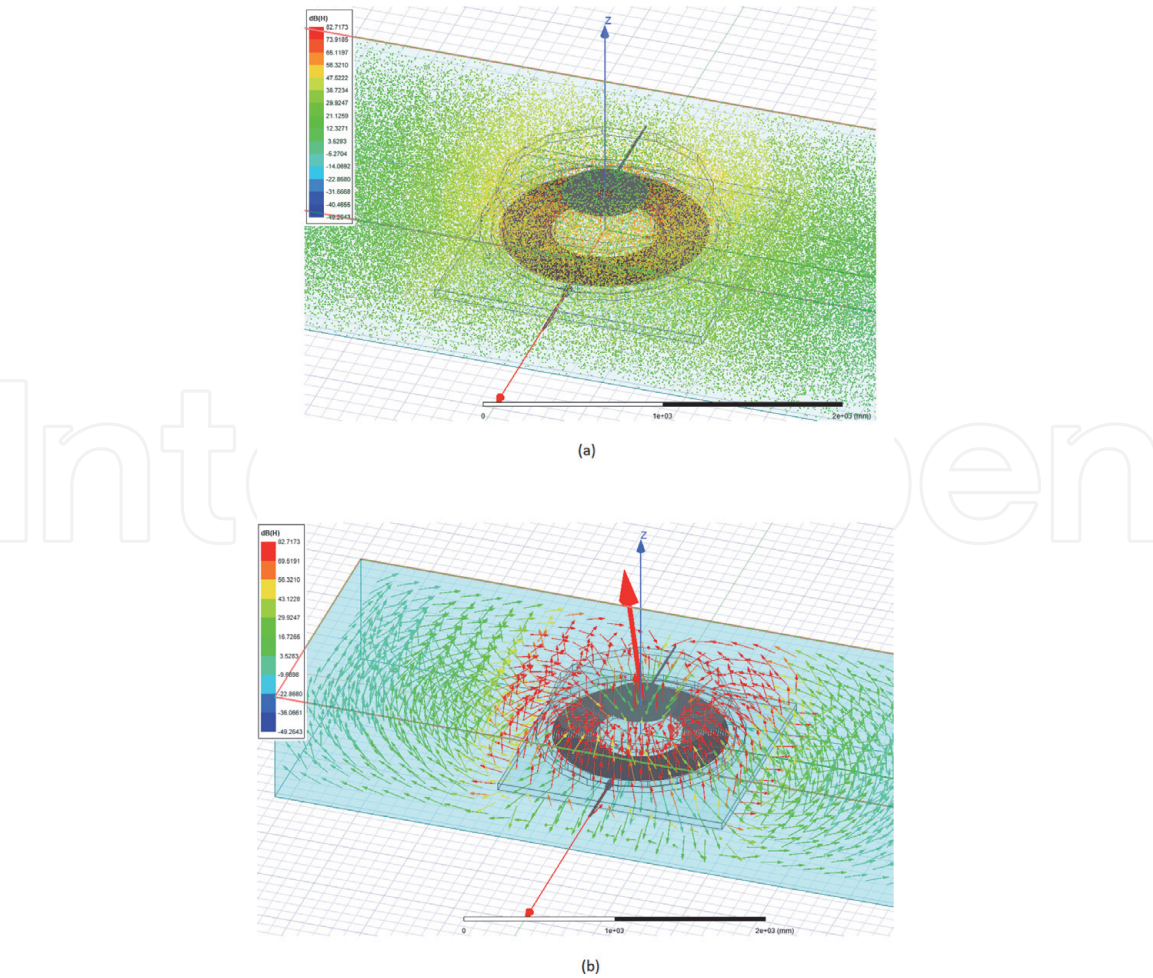


Figure 6. Magnetic field shown in ANSYS software simulation: (a) the diffusion and (b) the flux lines of the magnetic field.

maximised. The transmitter and receiver circuitry are made to resonate at the same frequency as shown in the equation below.

$$f_0 = \frac{1}{2\pi\sqrt{L_T C_T}} = \frac{1}{2\pi\sqrt{L_R C_R}} \tag{6}$$

where L_T, L_R are the coils and C_T, C_R are the capacitors of the transmitter and receiver, respectively. It is possible to achieve a high device efficiency by developing high-detailed transmitter and receiver coils, even if the system becomes less efficient the further the transmitter coil is away from the receiver.

As a whole, WPT (both IPT and CPT) throughput power decreases in a linear trend (for a log scale) with increasing frequency. It is likely that this limitation is primarily determined by power electronics limitations, rather than coupling characteristics, since it affects IPT and CPT equally. As the frequency increases, the output power is limited by losses. This limitation appears in both IPT and CPT applications. The average power is increased by 10-fold in the last 10 years, with the frequency also increased by 10-fold. In part, this is attributed to the development of wide bandgap devices and the refinement of coupling structures to minimise losses. It is expected that the power-frequency empirical limitation will continue to increase with time, essentially like a “Moore’s Law” trend or variant for WPT. In **Table 1**, there is a further summary between typical differences in the development between CPT and IPT.

2.2.2 Near-field WPT system in mid-range

When the distance between transmitter and receiver is smaller than the geometry of the transmitter, is indicated as a small-range WPT. As a practical rule, the mid-range refers to the situation when the gap is 2 to 3 times the size of either device involved in the power transfer.

Two coil systems are used for charging both portable and heavy power devices like powerbanks. An optimal alignment has the greatest coupling co-efficient where the coils are the same size and parallel to each other. The mutual inductance

	Inductive power transfer	Capacitive power transfer
Switching frequency	10 kHz ~ 10 MHz	100 kHz ~ 10 MHz
Coupling field	Magnetic	Electric
Foreign objects (metal)	Will generate heat	Will not generate heat
Material	Litz wires, ferrites	Copper/aluminium plates
Cost	High	Low
Safety	Good	Excellent
Size	Small	Large
Misalignment	Poor	Good
Efficiency	Excellent	Excellent
Voltage stress	Medium	High
Power level	High	Medium
Stationary or dynamic	Better for stationary	Both

Table 1.
Comparison between the capacitive power transfer and inductive power transfer.

declines as the ratio of the two coils' primary magnetic field decreases, particularly when there is a broad separation between the two coils.

Multiple coils in the transmitter, receiver, or in the middle are adopted essentially for two main reasons: (a) more degrees of freedom to maximise the efficiency and desensitise the link gain versus coupling factor; (b) highly coupled transmitter-repeater or repeater-receiver link work greatly as impedance matching elements at both sides. Although this last configuration requires four or more coils, it offers a better efficiency-distance than a three coils system [14]. For this reason, the three coil WPT is not very popular, unless the application has no space for additional coils.

Let us consider a four-coil resonator system with two intermediate repeaters coils called "2" and "3" where an impedance (capacitor) compensation Z_2 and Z_3 are connected to form LC resonators. As shown in **Figure 7**, the transmitter and receiver are referred as "1" and "4" respectively. It has been considered the transmitter R_T and the load impedance Z_{Load} having relatively low quality factor of $Q_T = Q_1$ and $Q_R = Q_4$. Considering only the parasitic resistance, much higher quality factor Q_2 and Q_3 can be achieved. With this new nomination, k_{23} will be much lower than k_{12} and k_{34} because the distance between the intermediate coils are usually larger than the geometry of the coils. In this way the cross coupling effect could be neglected because of either the low quality factor Q and the small coupling coefficient depicted in the **Figure 7** in yellowish green. Similar to the two-coil system, the figure of merit could be written as a generic Δ_{ij} for any two of the four coils:

$$\Delta_{ij} = \kappa_{ij}^2 Q_i Q_j \quad (7)$$

calling i and j the number of the referred coils. An important equation to notice in design of a multi-coils system comes from the impedance reflected from the all coils to the primary transmitter. Considering the Eq. (4) introduced in a two coil system, it is possible to write for each coil the reflected impedance:

$$\begin{cases} Z_{ref,3} = \frac{\omega^2 k_{34}^2 L_3 L_4}{Z_4 + Z_{Load}} \\ Z_{ref,2} = \frac{\omega^2 k_{23}^2 L_2 L_3}{Z_3} \\ Z_{ref,1} = \frac{\omega^2 k_{12}^2 L_1 L_2}{Z_2} \end{cases} \quad (8)$$

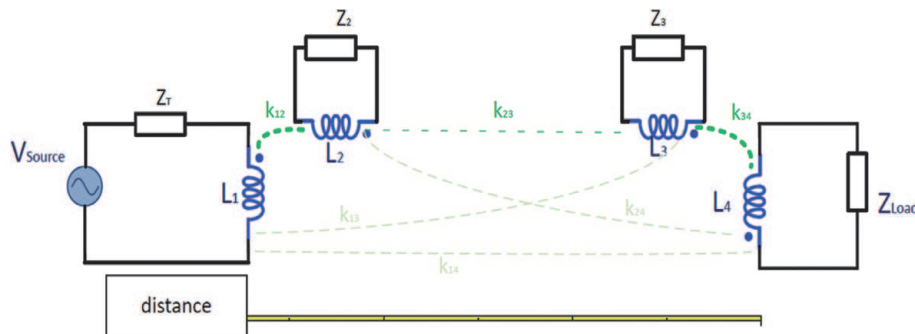


Figure 7. Four coils WPT system with the coupling factors. The couplings are marked following their value. κ_{13} , κ_{14} and κ_{24} are not visible because their intensity values are negligible.

Combining these equations in the Eq. (8)c, it is possible to obtain the impedance reflected in the primary transmitter:

$$Z_{ref,1} = \frac{\omega^2 k_{12}^2 L_1 L_2}{\frac{\omega^2 k_{23}^2 L_2 L_3}{\frac{\omega^2 k_{34}^2 L_3 L_4}{Z_4 + Z_{Load}} + Z_3} + Z_2} \quad (9)$$

where simplifying we obtain:

$$Z_{ref,1} = \frac{\omega^2 \left(\frac{k_{12} k_{34}}{k_{23}} \right)^2 L_1 L_4}{Z_4 + Z_{Load}} = \frac{\omega^2 k_{TOT}^2 L_1 L_4}{Z_4 + Z_{Load}} \quad (10)$$

In this equation we can notice that the reflected impedance of the all system depends directly only by the total coupling coefficient and the value of receiver impedance. Moreover, the WPT system can be seen as an equivalent total coupling coefficient defined by:

$$k_{TOT} = \frac{k_{12} k_{34}}{k_{23}} \quad (11)$$

It is a design rule making sure that the following condition can be met:

$$k_{TOT} = \frac{k_{12} k_{34}}{k_{23}} = 1 \quad (12)$$

the reflected load will be matched and we will have the maximum power transferred. In such a way, the four coils system creates a possibility to extend the distance from primary to the load using more and more coils. In order to maximise the transmission distance, the mutual coupling coefficient between the repeaters could be minimised. Additional intermediate coils with still be loose coupled between them but they will increase the total coupling coefficient of the system. For example, even if the coefficient k_{23} between the intermediate coils is loosely coupled to 0.01 because of the long transmission distance, the equivalent coupling coefficient k_{TOT} of the whole system can still be adjusted to 1 when both k_{12} and k_{34} are considered strongly coupled set to 0.1.

However, the impedance matching such a system is not endowed with a high overall efficiency because it is restricted by the merit factor given by the Eq. (9) Nonetheless, the four-coil system still offers (in terms of efficiency-distance) a better solution rather the two-coil systems when the distance is much bigger than the coil size.

2.2.3 Disadvantages

The power transfer in short transmission distance is commonly achievable with good coupling coefficient which depends on the medium between coils whether it is air or any material with permeability 1 or above. In addition, the best coupling coefficient is obtained when the coils have the same dimensions, negligible gap and they are perfectly aligned. The alignment of the transmitter not correct with the receiver has been the first challenge to overcome in this technology. Therefore, the charging appliance are usually fabricated in a similar size in order to have a visible matching. Although the system efficiency and power transferred can be maximised, the following problems can arise in these systems.



Figure 8.
FOD to a chew-gum aluminium wrap which have begun a fire.

Cross-talking or localised charging happens if the transmitter is much larger than the receiver. The magnetic flux path should only occur between the transmitter coil and the receiver coil. Only the transmitter coil that is closest to the receiver is powered on with others around in standby mode. This type of WPT are mostly used on dynamic EV charging applications where power consumption by each transmitter coil can be monitored to roughly identify the position of the receiving coil.

Not-alignment between primary-secondary coil is usually measured in degrees, from perfectly aligned 0° up to the coils orthogonally each other. Beyond the same size mentioned previously, another solution could be adopting a movable transmitter coil to align it at the position of the receiving coil which is detected through certain sensors. The transmitter coil will be moved to the place right beneath the receiving coil. This solution has a great potential in the stationary EV charging because precisely adjusting the position of vehicle is relatively difficult especially when the receiving coil is very small.

The foreign objects detection (FOD) near the transmitter coil or pad cause safety issue because of the eddy current created inside metallic objects. An increased temperature can be observed in daily metal objects such as coins, keys and metallic packaging materials. In **Figure 8** is shown the effect of a commercial chew-gum in its typical aluminium wrap. Eddy currents have increased temperature and a begin of fire have started.

3. Far-field wireless power transfer

In the far-field range, the power is transmitted through microwaves and in practice has been developed for low-power applications, because of its low efficiency. However, despite the low intensity the light rays are able to transmit the power. For instance, Sun rays can generate large amounts of energy in spite of travelling enormous distances. Similar to the other far field sources, the power generation occurs in specific conditions and in large amounts. A great use of this technique will be the solar farms in large areas of Saudi Arabia, which are able to generate nearly the same level of electricity per year compared to the traditional power generation stations [15].

The Radio Frequency (RF) signals have powered very low power application and is more considered as a harvesting energy solution. The ultrasound waves and vibrations are also utilised in similar applications. The waves are converted through

the piezoelectric effect as transducer for electrical signal and are considered as energy harvesting from the environment.

3.1 Microwave coupling

Microwaves are electromagnetic waves of frequencies ranging from 1 to 30 GHz. They are widely used in today's applications, especially in communications. Microwaves, differently from radio waves, can be sent in narrow beams, allowing the transmitter to concentrate its energy on the receiver. Microwaves are emitted or radiated from an antenna that is fed with a high frequency current in low power applications such as mobile phones. Another antenna will then pick up the microwaves and transform them back to an electric current.

The conversion of microwaves back to electricity was the biggest barrier to overcome in order to convert back the highest amounts of power. When an antenna picks up a microwave signal, it generates an alternating current of the same frequency as the microwave signal and equal to the microwave's signal strength. Since all applications and devices run on either an AC voltage of 50 Hz or 60 Hz or a constant DC voltage, the microwave antenna's high frequency current must be converted to a suitable voltage type. A great development of this technology was the invention of the 'rectenna' or 'rectifying antenna' by W. Brown. Using a rectifier, the rectenna converts the microwave antenna's high frequency current into a DC voltage. Further advancements in the semiconductor technology coupled with the availability of Schottky-barrier diodes resulted in higher efficiencies, higher power capabilities and smaller rectenna designs [16].

3.2 Rectifiers

The power efficiency, seen as Power Conversion Efficiency (PCE) in the **Figure 9**, is the capability of a rectifier to transform radio frequency (RF) energy into DC current. The PCE depends on the diode conduction and reverse leakage losses. The input voltage varies according to the frequency, which means the diode impedance varies, leading to a difference in the performance loss. In low input power, the efficiency is low because the input voltage dynamic is lower or equal to the forward biasing voltage of the diode.

In general, the PCE varies with the input dynamic which in turn depends on V_j , V_{br} , and R_L , representing the diode forward voltage drop (in the pn junction), the breakdown voltage and the dc load resistance of the rectenna, respectively. As shown in **Figure 10**, the efficiency sharply decreases as the voltage swings, when a diode exceeds V_{br} , the breakdown voltage. The peak efficiency is an optimum between: the forward (junction) loss and the reverse (breakdown) leakage loss. Moreover, the PCE is also affected by the production of higher order harmonics. Diodes produce harmonics and inter modulation as a result of their nonlinear nature, which reduces power conversion efficiency. Due to increased parasitic losses caused by harmonic generation, the power levels are reduced, which in turn

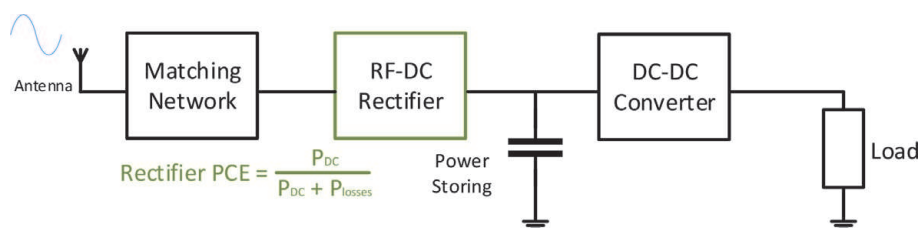


Figure 9.
Receiver block diagram where it has been highlighted the rectifier and its efficiency.

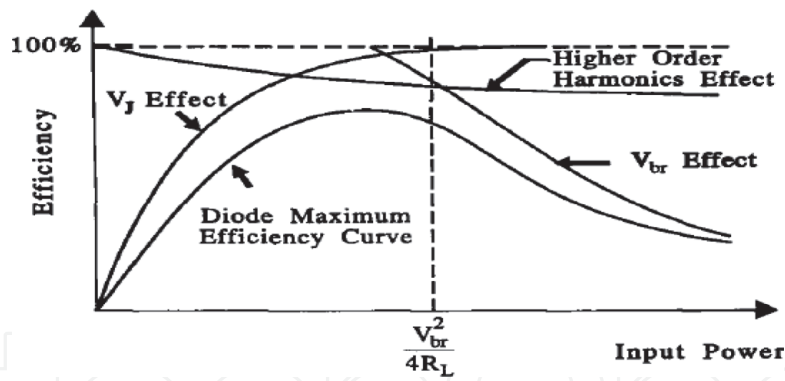


Figure 10.
Diode efficiency function depends on the breakdown voltage and the load resistance.

limits the performance. As a result, all of the above-mentioned parameters follow a tradeoff depending on the requirements. High threshold voltage diodes are favoured for low power applications, whereas high reverse break down voltage diodes are preferred for high power applications.

3.2.1 Diode rectifiers

Diode-based rectifier circuits are the most common because they have a lower forward voltage drop compared to the CMOS circuits. In rectenna applications, Schottky barrier diodes are widely used due to offering the best alternative to achieve higher PCE, a diode with a lower forward voltage.

The simplest rectifier circuit consists of a series shown in **Figure 11a** (or parallel in **Figure 11b**) and a parallel (or series) capacitor. The series diode circuit is also known as Villard Rectifier or DC restorer. The waveform produced is shown in **Figure 12a**. The parallel version is the well-known half-wave rectifier. When AC voltage comes through D1, only the positive cycle goes in the output, as shown in **Figure 12b**. Because of the reduction of the input, the full-wave rectifier, as shown in **Figure 11c**, is the most popular circuit. The output voltage sees two capacitors in series (each one is storing a voltage of Vpeak). Thus, Vout is a DC voltage twice the Vpeak, as shown in **Figure 12c**. For this reason this circuit is also known as a single-stage voltage doubler circuit or Cockroft Walton voltage doubler.

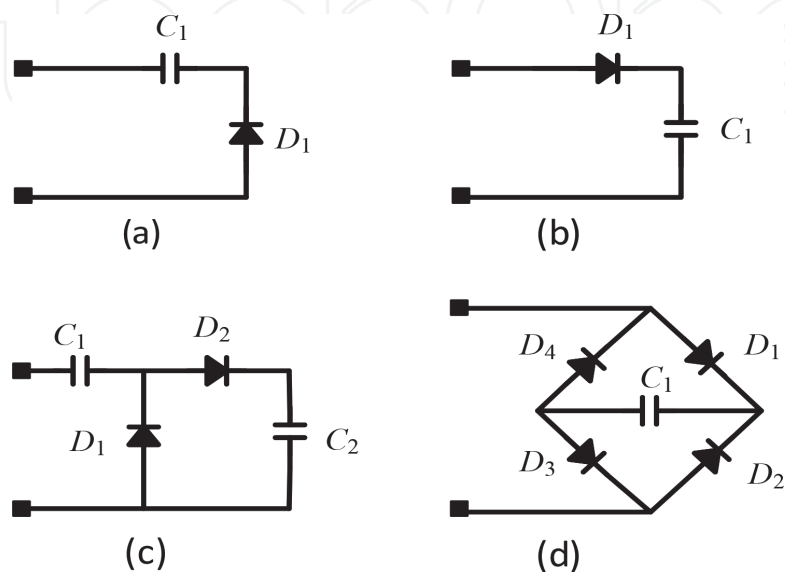


Figure 11.
The four typical configuration of the rectifier: (a) series, (b) parallel, (c) full-wave (d) bridge rectifier.

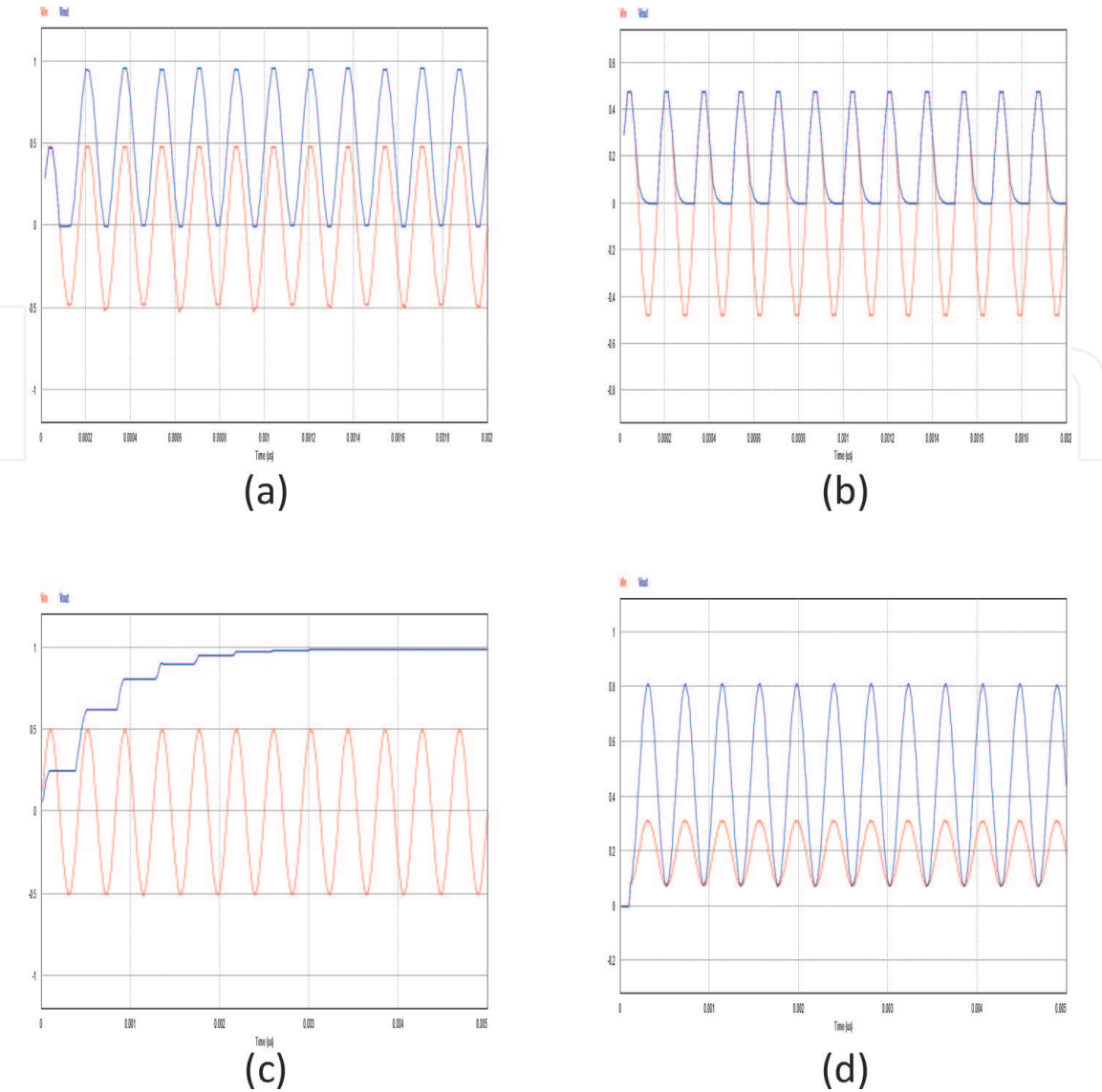


Figure 12. Voltage waveforms (y-axis) simulated towards time (x-axis). The input test is a 1 Volt peak-to-peak (10 kHz) voltage. For each configuration of the rectifier, the red colour represents the input voltage and the blue represents the output voltage, respectively: (a) series rectifier waveforms, (b) parallel rectifier waveforms, (c) full-wave rectifier waveforms, (d) bridge rectifier waveforms.

Therefore, this topology is more stable and efficient than the halfwave rectifier. There is also the bridge rectifier shown in **Figure 11d**, which rectifies both positive and negative. The figures in **Figure 12** summarise the waveforms obtained. As we can see, the full-wave and the Bridge rectifier “double” voltage have the highest output voltage, as shown in **Figure 12d**.

Different configuration of circuits that convert AC to DC by increasing the values goes with the name of voltage multiplier. The most fundamental configuration is the Cockcroft–Walton voltage multiplier shown in **Figure 13a**. This circuit’s operational principle is similar to the full-wave rectifier but has more stages for higher voltage gain. The Dickson multiplier in **Figure 13b** is a modification of Cockcroft–Walton’s configuration with stage capacitors being shunted to reduce parasitic effects. Thus, the Dickson multiplier is preferable for small voltage applications. However, it is challenging to obtain high PCE due to the fact that the high threshold voltage among diodes creates leakage current, thus reducing the overall efficiency. Additionally, for high resistance loads, output voltage drops drastically leading to low current supply to the load.

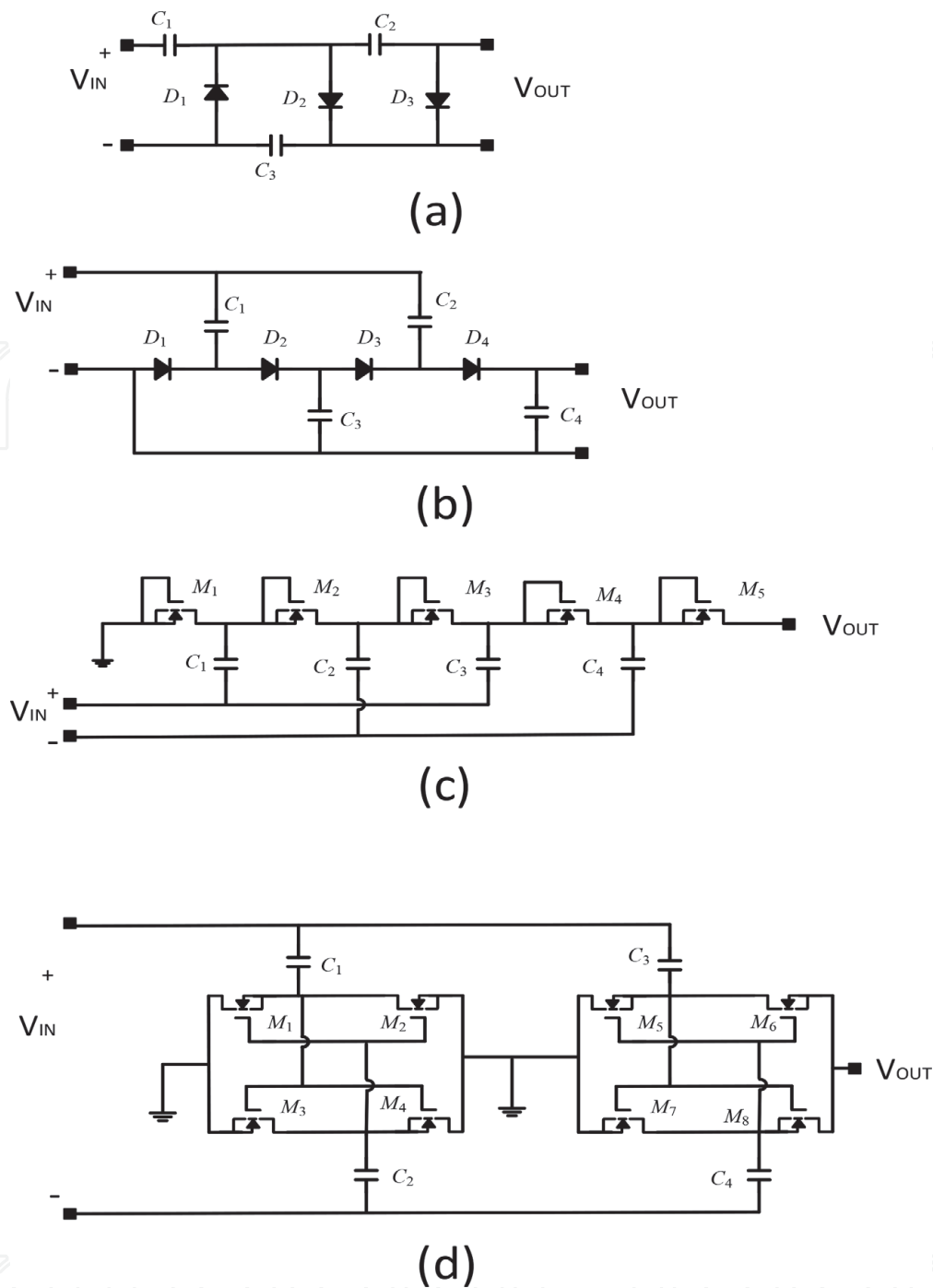


Figure 13. Most common voltage multiplier configurations: (a) three stages Cockcroft–Walton voltage multiplier, (b) four stages Dickson voltage multiplier, (c) four stage Dickson voltage multiplier using CMOS technology, (d) two stages voltage multiplier comprised of differential drive unit.

3.2.2 MOSFET rectifiers

Limitation of diodes can be overcome by MOSFET technology. Major advantage of MOSFET is the fast switching speed. Dickson charge pump is also designed using MOSFETs in order to merge it in integrated circuits as shown in **Figure 13c**. Relatively low threshold voltages and high PCEs are features of this design.

Moreover, differential drive voltage multiplier **Figure 13d** is widely used because of its low leakage current and potential for further modification in specific applications. The number of stages in a voltage multiplier has a close relationship with its sensitivity and efficiency. If the number of stages grows, the amount of losses per stage increases. However, the tradeoff consists of a higher voltage multiplication and small threshold voltage at the first stage. On the other hand, a voltage

multiplier with a few stages has less voltage drop between its stages, but it requires higher threshold voltage for all stages to work simultaneously. As a result, when a large number of stages are present, a voltage multiplier becomes more susceptible, whereas when smaller stages are present, it becomes more effective. Therefore, based on the implementation goals, the optimum number of steps should be considered.

The voltage loss across MOSFET devices leads to low efficiency. This is further deteriorated by reverse leakage current. Another major disadvantage of MOSFET based circuits is that as frequency increases, the efficiency decreases. This happens due to increased power losses from the reverse leakage current in the MOSFET.

4. Conclusions


The wireless power transfer technique has received a lot of research attention in recent years. As a result, it is becoming a more popular application in consumer electronics and electric cars. There are, however, other methods for transmitting electricity, which can be categorised further based on their working ranges, such as near-field and far-field transmission. This chapter provides an outline of the concepts of various methods of wireless power transfer. The investigation of the receiver block is then addressed by looking at the characteristics of rectifier technologies. Later in the book, the Rectenna device (rectifying antenna) is defined in relation to Internet of Things (IoT) wireless charging in remote locations.

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