TRILOGY

OF WIRELESS POWER TRANSFER

Basic principles, WPT Systems and Applications

2nd edition

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TRILOGY OF WIRELESS POWER TRANSFER

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WPT Systems and
Applications

CONTENT

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Part 1: Basic Principles

Introduction of Wireless Power Transfer

Wireless power transfer (WPT) is an emerging technology that can revolutionize industries and transform the consumers experience with small electronic devices. Take for example the way consumers use their smart phones, how this has changed in recent years, and how this is constantly evolving. This applies not only to all mobile devices but also to all electric appliances in industrial, medical, automotive and consumer areas with and without batteries. The user now expects devices that have high power demands with longer usage times. This means devices need either higher-capacity batteries that require to be charged less frequently or lower-capacity batteries that require more frequent charging. In either case, integrating wireless power transfer has a multitude of advantages that can revolutionize the way consumers use devices.

To be successful, wireless power transfer must be simple, convenient and intuitive to the user requiring the best possible performance (e.g. charge time, efficiency) compared to conventional connector technology. Achieving the best performance is reliant upon choosing the correct component for the application.

The basic principles of wireless power transfer are discussed in Part 1, which will lay the foundation for the remainder of the book. In this part, the various ways of wireless power transfer are described, with their advantages and disadvantages discussed. The different standards that define and regulate the use of these technologies are summarized. This includes the leading standards in addition to power classes which are currently not covered by the Wireless Power Consortium [1], AirFuel™ [2] and SAE J2954 [95]. These power classes can use different proprietary solutions, some of which are described. In the final section, the functionality of a wireless power transfer system is characterized with an equivalent circuit, definition of the resonance tank, coupling, efficiency, shielding and Spice simulations.

1.1 Wireless Power Transfer Methods

There are a variety of methods to transfer energy without direct physical contact. The field of wireless power transfer can be divided into several categories, dependent on the electromagnetic principle that is predominantly used (Figure 1.1). These technologies are discussed in the following sections.

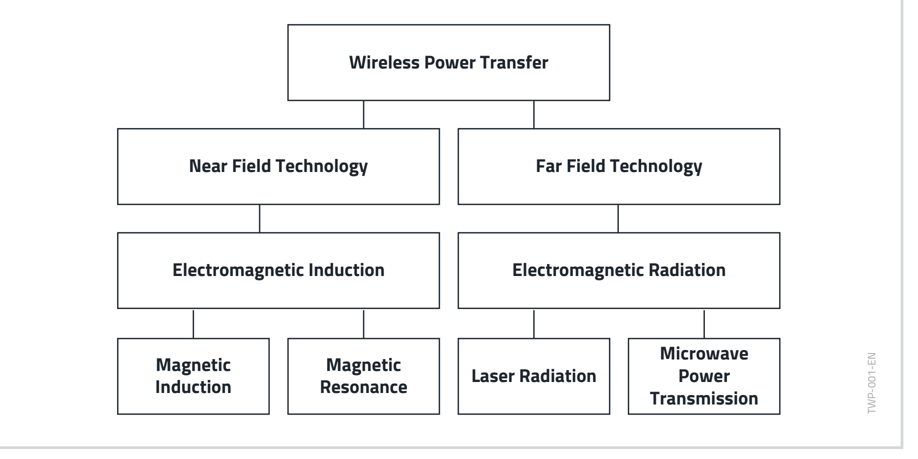

Fig. 1.1: Methods of wireless power transfer

1.1.1 Near-field Technology

Near-field wireless energy transfer can transmit energy using wire coils over a short distance. Near-field power transfer is a non-radiative power-transmission technique, but radiation losses may still occur due to lower efficiency. In the normal case, only ohmic losses occur.

Near-field technology is subdivided into the following categories:

- magnetic field
- electric field

Electromagnetic Resonance

Electromagnetic resonance or resonant inductive coupled power transfer have low coupling between the coil pairs. The galvanically insulated coils have huge stray inductances. One of the reasons for poor efficiency between two coils with low coupling is primary leakage inductance. This stray inductance requires a large induced voltage on the primary circuit. A higher current on the primary coil results in a higher induced voltage on the secondary side and greater losses are generated in both coils driven by Q factor. Therefore, it is common practice to compensate the secondary leakage inductance with a capacitance for inductive connections.

In order to compensate this leakage inductance, a capacitance is added in series or in parallel to the coil depending on the type of resonant topology of interest. Magnetic resonance or resonant inductive coupling is one of the most popular and efficient techniques for wireless power transfer and is used in a vast number of consumer devices, biomedical implants, electric mobility, material handling systems, lighting applications and contactless underwater power delivery. In figure 1.2 the functional block diagram is shown for electromagnetic resonance.

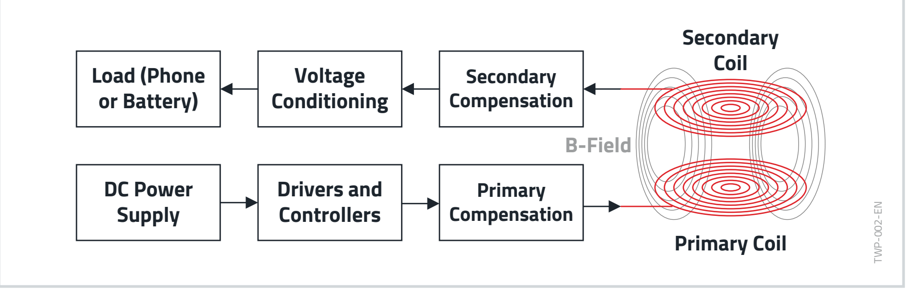

Fig. 1.2: Block diagram of a wireless power transfer system using electromagnetic resonance

Electromagnetic Induction

Wireless power transfer with electromagnetic induction in the near field works up to a distance of 1/6 of the wavelength of the transmission frequency, e.g typically up to 10 mm for smart-phone charging and up to 25 cm for electric vehicles. A straight conductor with a current flowing through it generates a magnetic field with a magnetic field strength H. When the wire is wound into a coil, the magnetic field is concentrated.

According to Ampere's law, the magnetic flux around a coil is directly proportional to the current flowing through the coil. The magnetic field strength of a coil is defined by the flux density. The more windings the coil has, the greater the magnetic field strength.

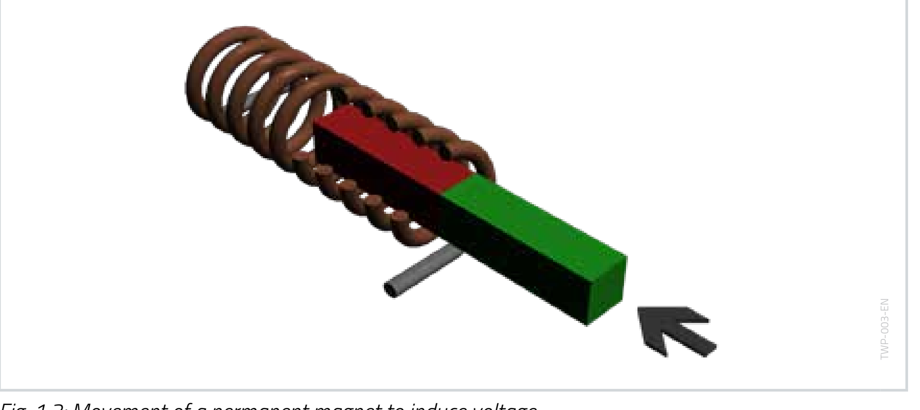

Fig. 1.3: Movement of a permanent magnet to induce voltage

It is also possible to place a permanent magnet inside the coil instead. A voltage is induced in the coil by movement of the permanent magnet's magnetic field (figure 1.3). A voltage is also induced when the coil is moved over the permanent magnet. Thus, voltage can be induced by moving the coil or changing the magnetic field. This process is called electromagnetic induction, which is the basic principle of a transformer.

If the two coils are not close enough to each other, then most of the primary magnetic flux does not flow through the secondary coil, resulting in poor coupling and leakage inductance. Leakage inductance is always present in a coupled coil system because the magnetic coupling of two coils is never 100 %. Based on the same principle it is also possible to transfer low energy with the so called NFC standard. The carrier frequency is 13.56 MHz and the delivered energy is less than 1 W. This way of energy transfer could be a very good alternative for low power applications.

Electrostatic Induction

Electrostatic induction, also known as capacitive coupling, is a method of transferring energy wireless between two electrodes that form a capacitance. A high-frequency alternating voltage is applied to the plates of the capacitor, which are close to each other. Electric fields are created and displacement current maintains the current stability. Thus, in this case the energy carrier media is the electric field.

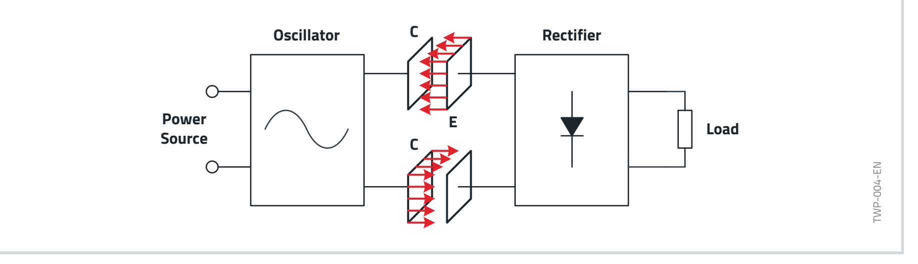

Fig. 1.4: Wireless power transfer with an E-field

1.1.2 Far-field Technology

With far-field technology, energy can be transmitted over greater distances, often more than several kilometers. The distances are much larger than the outer diameters of the antennas used. The far-field technology is not used in the industry because it is not ready for end-user products. It will be described in the next sections but not in depth. If more detailed information are needed please check publications from William C. Brown.

Examples of wireless power transfer techniques using far fields are:

- Microwave Power Transmission
- Laser radiation

Microwave Power Transmission

The process of microwave power transmission involves conversion of electrical energy into microwaves and transmission of the waves via an antenna. The transmitted microwaves are converted into conventional electrical energy at the receiver.

The following steps are necessary:

- Conversion of electrical energy into microwaves using a magnetron
- Reception of microwave energy using a rectifier and an antenna
- Conversion of microwave energy into electrical energy

William C. Brown, a pioneer in the field of wireless power transfer, designed and developed a system to demonstrate how energy can be transferred via free space with microwaves. [3]

Laser Radiation

Laser radiation is the wireless power transfer of photonic energy (heat or electricity) from the transmitter to the receiver using a laser with usable form as either heat or electricity. The same transmission method is used for the production of solar energy, whereby the sun's rays hit solar cells and convert the sunlight into solar and electrical energy. This way of energy transfer is classified as an energy harvester. A special photovoltaic cell converts the laser beams into energy. The photon energy has a higher intensity than sunlight, enabling a targeted orientation to specific locations, and can deliver energy 24 hours a day. This energy can be transmitted via air, free space or optical conductors.

The advantages of laser radiation:

- The narrow bandwidth radiation allows a high energy concentration over long distances up to several kilometers
- The receivers are very small and can be easily integrated into existing devices
- The power can be transmitted without high-frequency interference (e. g. WLAN or LTE)
- Laser radiation can use any available energy source for the laser
- Energy can be transmitted via free space or optical conductors

The disadvantages of laser radiation:

- Safety. Assure that no objects are in the beam
- Poor efficiency
- Transmitter and receiver must have line-of-sight contact
- The efficiency of the system depends on the weather conditions

1.2 Wireless Power Transfer Standards

Although the resonant and inductive technique are the most usable methodologies of wireless power transfer, there remain specifics that need to be agreed to ensure interoperability. The success of a contactless energy transfer solution depends on both the transmitter and receiver device adhering to a standard. Only if the devices operate within specific tolerances can they be operated with each other independently of the manufacturer, increasing the adoption of the standard. What are the standard approaches and what is the technology behind them?

There are two low power wireless power standards for consumer products; the Qi (chee means flowing energy) Wireless Power Consortium standard [4] and the AirFuel™ standard [5]. Additionally one high power standard has been established: SAE J2954.

	AirFuel™	Wireless Power Consortium	SAE J2954	NFC Forum
Power	1.5 W–50 W	5W BPP, 15 W EPP, 15 W MPP LEV 100 W and 500 W Industry 30–300 W, 300–1 kW, 1 kW–3 kW KI 1.35 kW and 2.2 kW	3.7 kW/ 7.7 kW/ 11 KW	1 W
Placement	Any operation, any placement	Specific placement	Specific placement	Any placement
Multiple devices	Yes, incl. various power	One device at a time	One device at a time	Yes
Operating Principle	Resonance	Inductive, some resonance	Inductive	Resonance
Communications	Bluetooth Low Energy	In-Band	Wifi, Bluetooth	RF band

Tab. 1.1: Wireless Power Transfer Standards

1.2.1 Wireless Power Consortium

The basis of the Qi standard is the induction coil where a high frequency transformer of a power converter is split into two separable parts and operates in the frequency range from 100 kHz through 205 kHz. This standard is characterized by its tight coupling between the two coils and as such requires precise alignment between the coils. One device (receiver) can be charged on one transmitter at any time. According to the current (2023) released specification of the Qi standard there are two power levels. Basic Power Profile (BPP) with 5 W and Extended Power Profile (EPP) and Medium Power Profile (MPP) with 15 W. The WPC is working to add standards for higher power levels like power levels up to 500 W intended for light electric vehicle and industrial application (intended for e.g. laptops) and up to 3.0 kW (based on the specification). The most popular Qi based application has been the smartphone charger. The Qi standard uses in-band communications to ensure proper device detection and safe operation. Updated converter designs have targeted the improvement of efficiency and overall performance.

Characteristics:

- Power transmission with inductive coupling over short distance (up to 10 mm)
- Transmitter (Tx) and receiver (Rx) coils are inductively coupled
- The magnetic field is concentrated in the narrow area between the transmitter and receiver coil
- Each transmitter can support one receiver
- Various power classes up to 3 kW
- Frequency range 100–205 kHz/360 kHz
- Coil shapes: wound on ferrite or on printed circuit board (PCB)
- The most established solution worldwide after big global players decided to use the Qi standard in their products

1.2.2 AirFuel

The AirFuel standard operates in the license-free ISM band of 6.78 MHz. The basic system architecture is similar to the Qi standard but the coil structure is completely different. The AirFuel standard operates the coils as loosely coupled, leading to a high leakage for the transformer model. To overcome the leakage, resonance is used to enhance the current in the magnetizing inductance of the transformer model that in turn generates the magnetic field [6, 7]. This makes the coil structure less susceptible to leakage fields allowing it to share its magnetic field with multiple receivers. This in turn allows systems to power multiple devices of various power levels simultaneously without the need for precise alignment. The present AirFuel standard supports a wide range of power levels to address the multitude of device sizes from 1.5 W through 50 W while the technology itself has been demonstrated at even higher power levels up to 130 W [8]. Due to the ISM band bandwidth restriction of ±15 kHz, in-band communications becomes impractical, so the Bluetooth Low Energy (BLE) standard is used for communications between the source and device to establish proper operation. Additionlly the AirFuel RF can transfer low power energy over the RF band.

Characteristics:

- Accommodates spatial freedom with greater distance in the z-direction (50 mm) and no exact positioning of the receiver is necessary
- One transmitter can power multiple receivers simultaneously
- Frequency ranges: energy 6.78 MHz (ISM band), data 2.4 GHz (BTLE)
- Currently not many commercial products in high volumes as mobile phone suppliers decided to go with Qi

1.2.3 NFC standard

The NFC standard allows the transfer of energy at 13.56 MHz with a maximum power of 1–2 W. The system must have a 50 Ohm impedance matching and works in the same way like the AirFuel technology. Target will be IoT devices or all other applications with a low power charging need or low power during operation.

Characteristics:

- Spatial freedom with distances up to 100 mm and no exact positioning of the transmitter and receiver needed
- One transmitter can power multiple receiver simultaneously
- Frequency range: energy and data transfer at 13.56MHz
- Very new, no products in the market,

1.2.4 SAE J2954

The SAE J2954 establishes an industry-wide specification that defines acceptable criteria for interoperability, electromagnetic compatibility, EMF, minimum performance, safety, and testing for wireless charging of light-duty electric and plug-in electric vehicles. The specification defines various power levels. The specification supports home (private) charging and public wireless charging.

1.2.5 Proprietary System Solutions

All standards have their advantages and disadvantages. Approximately 50 % of applications in industrial or medical sectors are not dependent on being compatible with other manufacturers or other appliances. With no need of compatibility, manufacturers from all sectors, with the exception of the consumer electronics and automotive industries, are developing proprietary system solutions in-house.

These proprietary solutions do not always require customer-specific passive components for wireless power transmission. Indeed, not using a standard offer the greatest flexibility with the WE-WPCC standard transmitter and receiver coils, allowing custom power levels and physical dimensions.

Two application examples are shown in Part 3 of this book. A purely discrete circuit up to 100 W followed by an example up to 200 W including data communication.