APPLICATION NOTE

ANP014 | Wireless Energy Transmission Coils as Key Components

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1. INTRODUCTION

Why is wireless energy transmission gaining importance now even though the technical principle is over 120 years old? The behavior of smartphone and tablet users has changed dramatically over the past years. People are constantly sending emails, texting, posting on social networks and playing online games. The average user can barely last a day on a single battery charge, because large displays, fast processors and HD graphics consume lots of power. Public wireless charging stations offer a convenient solution to this problem. For example, a user can charge a smartphone by simply placing it on a restaurant table outfitted with a wireless charger. To make the user's experience successful, the charger must be easy to use, fast and efficient, but more importantly, its performance must be comparable to conventional wired chargers.

Driven in part by Apple's entry into the Wireless Power Consortium (WPC), this technology has become well established, particularly in the smartphone sector. In addition, a wide range of applications across various industrial fields is expected to follow.

For example, in the medical field, charger contacts, such as plugs or prongs, corrode easily with liquid disinfectants. However, with integrated wireless charging technology, medical instruments can be completely encapsulated which prevents contamination and corrosion. Moreover, in industrial settings with high concentrations of dirt, dust or flammable materials, wireless power supplies can eliminate many of the risks and quality control issues associated with charger contacts. The development of autonomous mobile robots in industry (AMR, AGV), as well as electric vehicles, suggests that this technology will also gain traction in these areas, extending to higher power classes (up to 11 kW).

2. THE STANDARDS FOR WIRELESS POWER TRANSFER

The success of these solutions depends, of course, on devices that adhere to standard compatible protocols on both the transmitter and receiver sides. Therefore, regardless of manufacturer, once it is certain that devices can be charged at any compatible station, the technology will become popular. Hence, it is critical to understand which standard protocols are present in the market and the technology behind them.

2.1 Close-coupled Qi Standard Wireless Power Consortium (WPC)

- Energy transmission through inductive coupling over a short distance –typically in the millimeter range.
- Transmitters (T_x) and receivers (R_x) are coils coupled via a magnetic field.
- The magnetic field is concentrated in a small area between the transmitter and receiver coils.
- A single transmitter can only supply energy to one receiver at a time.
- Frequency range consists of 100 – 360 kHz.
- Coil shapes and form factors consist of wire wounds on ferrite or traces printed on a circuit board.
- At time of writing, the WPC has defined three power profiles in the smartphone sector:
  - **Baseline Power Profile (BPP):** Supports up to 5 W
  - **Extended Power Profile (EPP):** Supports up to 15 W
  - **Magnetic Power Profile (MPP / Qi2):** Provides up to 25 W (with future versions planned to support up to 50 W)
- **KI standard for wireless kitchen appliances:**
  - Power range from 100 W up to 2.2 kW
  - First devices are expected to enter the market in 2026
- **Mid-power standard:** The WPC is also working on a future standard for devices or vehicles (e.g., laptops, drones, e-scooters) in the 30–200 W range

2.2 Loosely coupled (Magnetic Resonance) - Airfuel Alliance

- The transmitting coil supplies energy at a frequency resonant with the receiving coil. The receiver is tuned to the resonant frequency to efficiently receive the energy. This phenomenon is called magnetic resonance.
- Works at large distances in the z direction –typically 50 millimeters.
- No precise positioning of the receiver is necessary – vertical, horizontal placement is not critical.
- One transmitter can supply energy to more than one receiver at the same time.
- Frequency range for charging energy is 6.78 MHz (ISM band), data 2.4 GHz (LP Bluetooth).
- No commercial product on the market yet.
- No compatibility with Qi standard of WPC.
- There are two power classes:
  - **AirFuel Resonant:** Enables simultaneous charging of multiple devices on a single surface with power levels of up to 50 W.
  - **AirFuel RF:** Specialized for very low power levels (mW to a few watts) over longer distances, targeting IoT sensors and wearables.

2.3 NFC Forum

- NFC Wireless Charging (WLC):
  A standard defined by the NFC Forum for extremely compact devices (e.g., styluses, trackers, electronic shelf labels in retail), typically supporting power levels below 1 W up to 3 W.
- Power transfer via standard NFC antennas and chipsets.
- **The NFC Wireless Charging 2.0 specification** has recently reached the Final Draft International Standard (FDIS) stage within ISO and is expected to be adopted shortly by the International Electrotechnical Commission (IEC) / Technical Committee 100. It will thus be globally recognized as part of the IEC 63652 standard.

2.4 Standard for Electric Vehicles (EV)

Specific standards exist for wireless power transfer in electric vehicles (EVs), covering power levels up to 11 kW (and beyond).

- **SAE J2954:** The leading standard from SAE International for passenger vehicles.
  - **WPT1:** Up to 3.7 kW
  - **WPT2:** Up to 7.7 kW
  - **WPT3:** Up to 11 kW
- **IEC 61980:** An international series of standards (often adopted as EN IEC 61980) that defines general requirements and communication protocols for wireless power transfer systems in electric vehicles.

At time of writing there are still no commercially available vehicles on the market that fully comply with these standards. The industry continues to focus primarily on cable-based charging infrastructure. However, increasing damage (e.g., due to vandalism) and the mechanical robustness of WPT solutions (e.g., transmitter coils embedded beneath asphalt) could drive a shift toward wireless systems. For broader adoption, however, participation from EV manufacturers—particularly from Asia—will be essential.

Moreover, there is a multitude of customized solutions on the market with specific power ratings. The main application areas are power supplies for industrial equipment and large battery charging. These are mostly inductive solutions with small and medium production volumes that are not compatible among them and require their own unique approvals and certifications.

3. THE QI SYSTEM

How is the WPC Qi standard structured? The low power class solution consists of a transmitter that provides 5 W to the receiver coil. The transmitter and receiver communicate via a specific power management protocol (Figure 1).

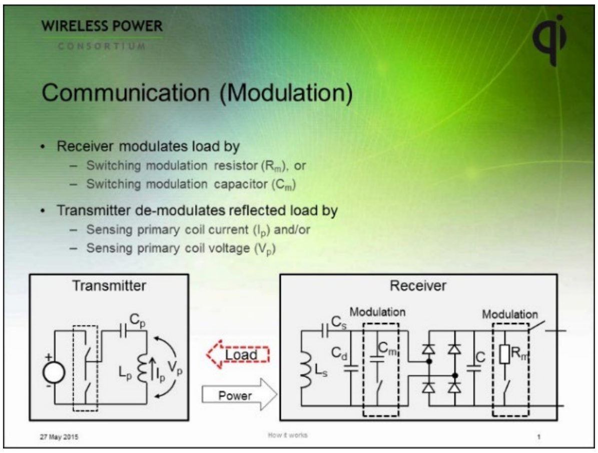

Figure 1: Principles of the WPC Qi standard.

The power is delivered between the coils at an operating frequency range of 100 – 360 kHz. The receiver requests the required energy from the transmitter and the transmitter adjusts to the request. The energy transmission is monitored and adapted by the power management system. If the receiver does not need any more energy, the system goes into standby mode. Semiconductor manufacturers offer designers evaluation kits and reference designs. For example, here is a picture of the receiver board WPR1500-HVMPP from NXP (Figure 2). The receiver coils suitable for the application are available from Würth Elektronik's product portfolio.

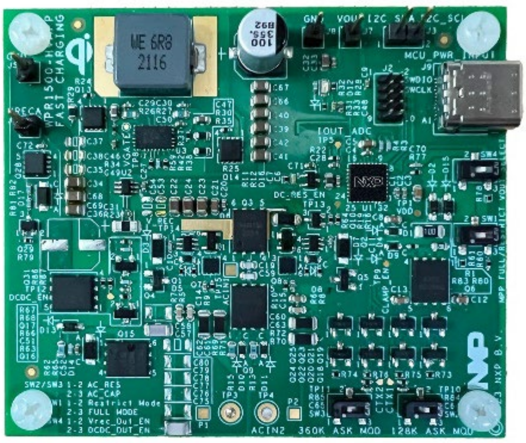

Figure 2: Receiver board WPR1500-HVMPP form NXP.

The characteristics of the transmitter and receiver coils are crucial to achieve low power transmission losses. The proper selection (Figure 3) and positioning of the transmission and receiver coils have a major influence on the efficiency of the energy transmission.

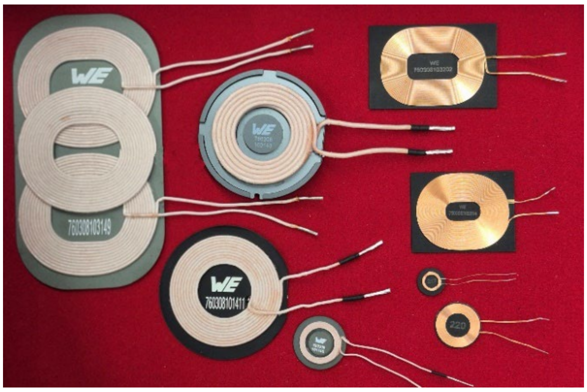

Figure 3: Selection of transmission and receiver coils offered by Würth Elektronics Midcom.

4. KEY FACTORS FOR THE COILS

A series of key factors dictate the best possible solution for low loss energy transmission.

4.1 Placement of the coils

The transmission and receiver coils need to be properly aligned to minimize losses. Lateral, canted and vertical misalignments are particularly detrimental to energy transmission. (Figure 4).

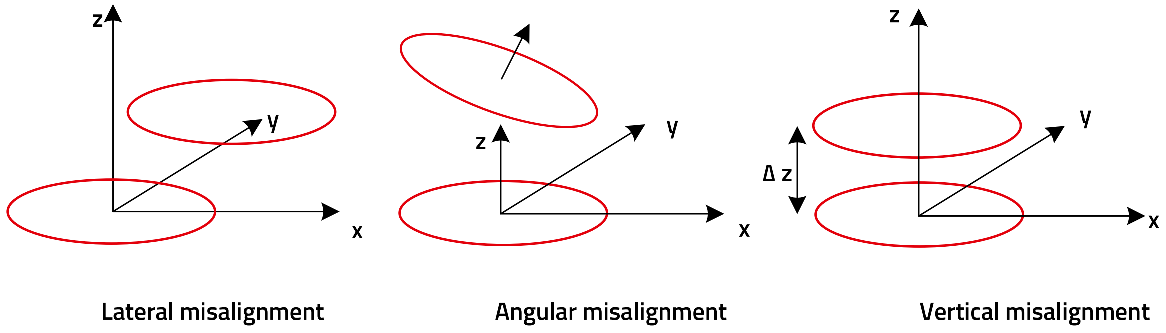

Figure 4: Types of transmission and receiver coil misalignments.

Good coupling and maximum energy transmission depend on the size of the effective area of the receiver coil in the magnetic field of the transmitter coil. Moreover, it also depends on the distance in the z direction. If the receiver coil is centered with the receiver coil without canting and the distance in the z direction is as low as possible then it is more likely that transmission losses are minimal. A coupling factor of 1 is ideal. This means, the effective area of the transmission and reception coils is equal.

4.2 Coupling

To compensate for misalignment losses, it is important to design coils with high quality and coupling factors.

The coupling factor between the transmission and receiver coils consists of the following parameters:

$$k = \sqrt{k_1 \cdot k_2} = \frac{M}{\sqrt{L_1 \cdot L_2}} \qquad (1)$$

L_1 and L_2 are the self-inductances of the coils. M is the mutual inductance between the two coils. The quality factor of the coils depends on the resistance loss R_L and the reactance X_L.

$$Q_L = \frac{X_L}{R_L} = \frac{\omega_0 \cdot L}{R_L} \qquad (2)$$

Air coils with ferrite plates have a typical quality factor of between 100 and 300. The resistance in the coils and also the ohmic resistance of the wire are influenced by various factors.

4.3 Skin Effect

The skin effect (current displacement) occurs in electrical conductors carrying high-frequency alternating current and depends on the frequency of the AC. When the frequency of the alternating current increases, then the concentration of current on the surface of the conductor also increases. Therefore, high frequency alternating currents displace or "push" the majority of the current to the surface. In such cases, the current density in the center of the conductor is lower than on its surface. The penetration depth δ can be described with the following formula:

$$\delta = \sqrt{\frac{2\rho}{\omega \cdot \mu}} \qquad (3)$$

ρ	specific resistance
ω	angular frequency
μ	sheared effective permeability (e.g.: 100)

The penetration depth is measured from the outer diameter to the center of the conductor and for a frequency of 50 Hz the penetration depth is approximately 10.4 mm, at 10 kHz 0.73 mm and at 100 kHz 0.23 mm. From these calculations, it is evident that the skin effect reduces the area through which the current flows, and consequently, the resistance seen by the current flowing through this smaller area rises. Higher resistance means higher energy losses.

By using high-frequency wire strands in the transmission and receiver coils, the energy losses from the skin effect can be significantly reduced. High-frequency wires consist of thin wires braided in groups of two or more wires. Each of the wires in the group carries a portion of the total current. This helps minimize the skin effect, and hence, more energy can be used effectively.

4.4 Proximity Effect

Another factor that influences the energy losses in the coils is the proximity effect. The proximity effect causes current constriction or current displacement in closely spaced conductors as a result of the magnetic flux leakage in each of the conductors. Wire strand configuration, winding technology and the structure of wire insulation can reduce unwanted eddy currents in the coils.

4.5 Loss Factor

Wireless energy transmission is limited by the loss factor in the system. The loss factor λ is defined as:

$$\lambda = \frac{P_{loss}}{P_{out}} \qquad (4)$$

This ratio expresses the total loss of energy to the transmitted quantity of energy. The main goal is to minimize the loss factor in the system as much as possible. If the transmitter and receiver coil configuration is optimized, a minimal loss factor can be achieved. However, the loss factor is still inherently affected by the quality factor and coupling factor of the system as a whole.

$$\lambda_{min} = \frac{2}{(k \cdot Q)^2}\left(1 + \sqrt{1 + (k \cdot Q)^2}\right) \qquad (5)$$

The equation shows that the product of quality factor and coupling factor can be taken as the system quality factor (figure of merit, FOM). Deterioration of the loss factor, e.g. due to a poor coupling factor, can be compensated by raising the quality factor of the coils. (Figure 5)

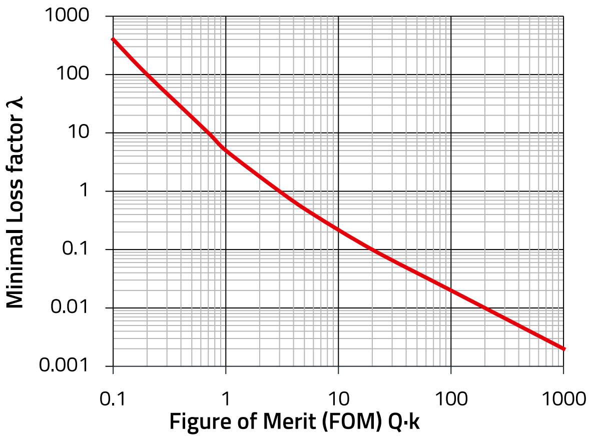

Figure 5: Correlation between the loss factor and the figure of merit.

4.6 Field pattern

Another important element that crucially influences the coils efficiency is the magnetic field pattern. The magnetic field pattern determines the unwanted radiation into the surroundings. Unwanted radiation into the surroundings has significant effect in system efficiency.

Figure 6 shows the magnetic field strength and Figure 7 shows the magnetic flux density of the transmission and receiver coils in optimal coupling.

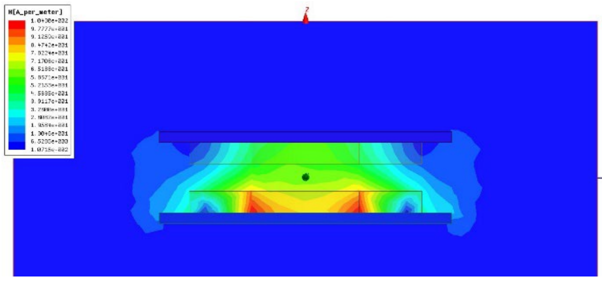

Figure 6: Simulation of the magnetic field strength in inductively coupled coils on ferrite.

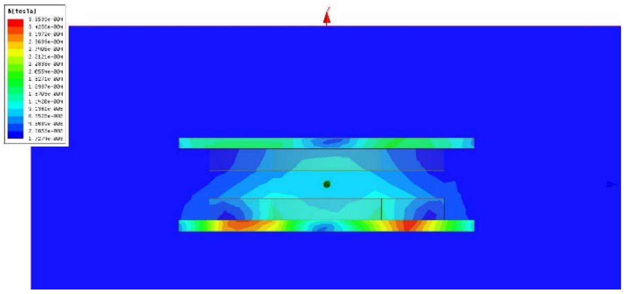

Figure 7: Simulation of the magnetic flux density in inductively coupled coils on ferrite.

It is clear that the magnetic field is selectively limited to the space between the coils and there is practically no influence on the surroundings. The simulation of the flux density shows the effect of the ferrite plate. The magnetic flux is concentrated within the ferrite. Figure 8 shows the magnetic field strength and Figure 9 shows flux density with a lateral misalignment (28%) of the transmission and receiver coils.

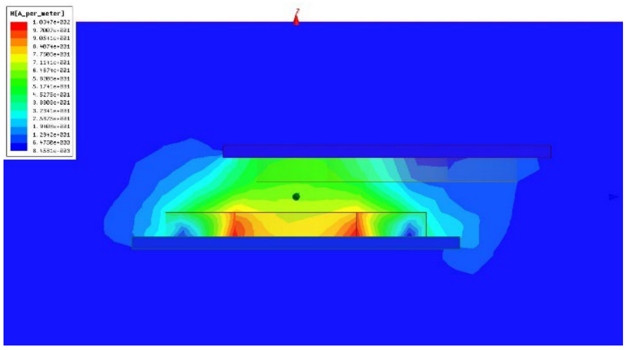

Figure 8: Simulation of the magnetic field strength with a lateral misalignment (28%) of the transmission and receiver coils.

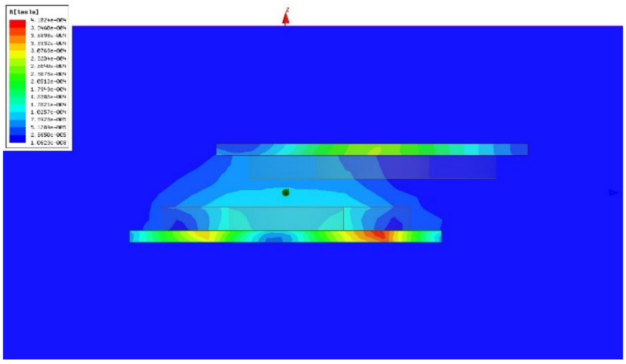

Figure 9: Simulation of the flux density with a lateral misalignment (28%) of the transmission and receiver coils.

With this misalignment, the magnetic field and magnetic flux are mainly limited to the overall configuration of both coils. There is no increase of the field in the z-direction. It can be deduced that by using a suitable ferrite shield, the magnetic field in the inductive coupling is limited to the area between the coils, and therefore, additional shielding measures are not necessary.

In addition, the Qi standard regulations prevent greater losses arising from misalignment of the coils. For example, if the energy transmission efficiency of the connection drops below 70%, then the power management system aborts transmission. Only when the alignment of the coils allows for energy transmission with an efficiency >70%, then energy transmission starts.

Moreover, the geometries and materials of the transmission coil are specified in detail in the WPC Qi standard. Since the components, such as the transmission coils, power management system and chipset, need to comply with the standard, then interoperability of the overall system can be guaranteed. Qi certification of devices involves independent test laboratories verifying interoperability of new products with previously certified devices.

The WPC has defined different designs for various power classes and applications stipulated in the Qi standard for the transmission coils. These designs are divided into two classes. One class consists of designs with ferrite plates and wound wire coils. The other class consists of circuit boards with printed windings or hybrid solutions. Within each class, the coils are classified by number of coils (single, array), size, shape, voltage and the type of control mechanism (voltage, duty cycle, frequency). In addition, Qi2 (MPP) designs feature a ring of magnets surrounding the coil. This is based on Apple's MagSafe principle. The ring is designed to automatically align the receiver with the transmitter coil. The permanent magnet is intended to automatically center very lightweight receivers on the transmission coil.

4.7 Improvement and optimization of the standard coils

The parasitic resistances in the coils can be minimized by using high-quality materials, designing efficient wire strand insulations and optimizing winding technologies. Improvements in these areas ultimately increase the quality factor of the system. Such efficient coils provide better performance in industrial or medical applications. Würth Elektronik offers a wide range of transmission and receiver coils that meet the Qi requirements with a low R_{DC} and a high-quality factor.

5. SUMMARY

Wireless energy transmission is most effective when it complies with a clearly defined standard. In particular, in the Qi standard there are various ways of positively influence the energy transmission of the coils. The selection of optimized coils, careful system design and clear guidance for the user in placing the device on the transmission station can constitute a competitive advantage for the device manufacturer. From the standardization body perspective, better optimization definitions are a work in progress that should lead to an improvement in the performance of the next system generation. Nevertheless, the transmission and receiver coils remain the key components in wireless energy transmission and are essential for the overall system efficiency. For more detailed and in-depth information on the topic, we also recommend taking a look at Würth Elektronik's "Trilogy of Wireless Power Transfer."

A APPENDIX

A.1 Literature

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