

Resonant wireless power transfer

Abstract

Our mobile devices are becoming more and more wireless. While data transfer of mobile devices is already wireless, charging is typically still performed with cables. Efficient and easy-to-use wireless charging is the next major step in freeing our devices from their wired connections. Current inductive wireless charging designs work, but the receiver must be positioned very accurately on the charging pad for efficient power transfer to actually take place. Resonant wireless charging is much more forgiving of the receiver placement - as long as the receiver is placed somewhere on the resonant wireless charging pad, power transfer can be established.

Resonant wireless charging design needs more than simply an understanding of the properties of the switches. An efficient design also requires knowledge of how the magnetic system works. The central part of optimizing the wireless charging system during the design phase is applying the formula used to calculate the resistance seen by the transmitter and estimating the maximum power that can be transmitted. In addition, the coupling between the transmitter and the receiver, and the effects that the quality factors of the two coils have on the overall efficiency must be understood.

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1 Operation principle

Figure 1 shows a wireless power transfer system with two magnetically-coupled coils. In the transmitter coil, the electric energy is converted to magnetic energy which is picked up in the receiver coil where it is converted back to electrical energy.

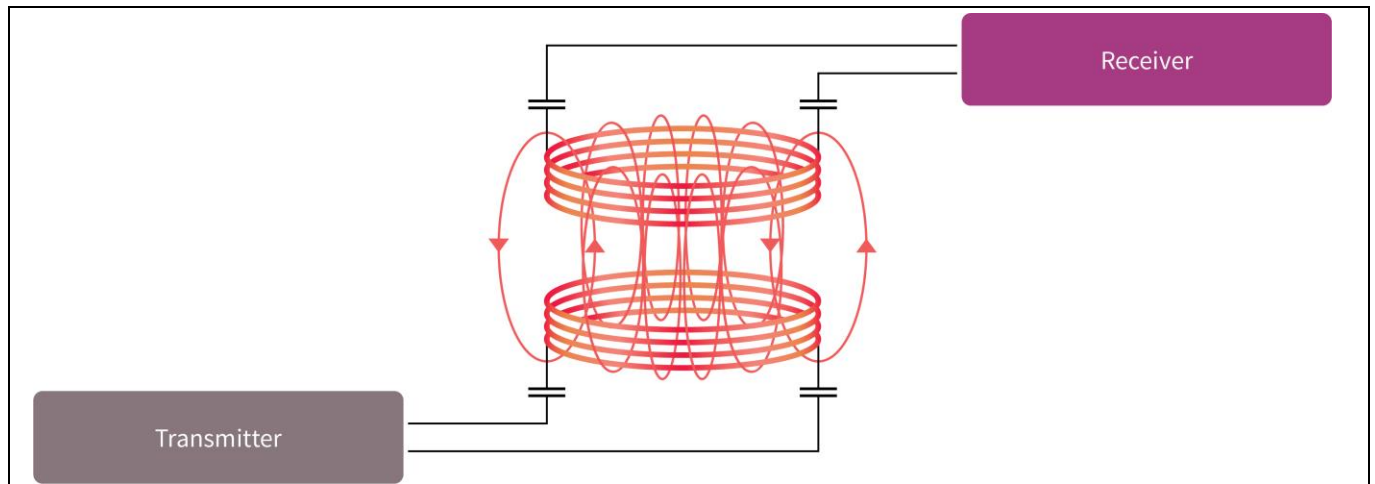


Figure 1 A resonant wireless power transfer system consists of a driven LC-resonator on the transmitter side and another LC-resonator on the receiver side

Inductive wireless power transfer (WPT) is limited to just a couple of millimeters distance between the transmitter and the receiver. With gaps in the centimeter range, the coupling decreases and with it, the energy transfer efficiency drops. Working with air gaps in the centimeter range requires a resonant scheme using coupled resonant coils that can cope with low coupling factors. The AirFuel Alliance defined a standard for resonant WPT which operates at a frequency of 6.78 MHz and allows charging of multiple devices simultaneously.

The AirFuel standard defines coupled resonant coils for the wireless energy transfer, as illustrated in Figure 2. The transmitter is an LC-series resonator consisting of the capacitor C_T , the coil with inductance L_T and an effective series resistance R_T . The receiver is another LC-series resonator with the capacitor C_R and the coil (L_R and R_R). The load resistance (R_L) is attached to the receiver. For the energy transfer, there is a coupling between the coil of the transmitter and the coil of the receiver, where M is the mutual inductance of the system.

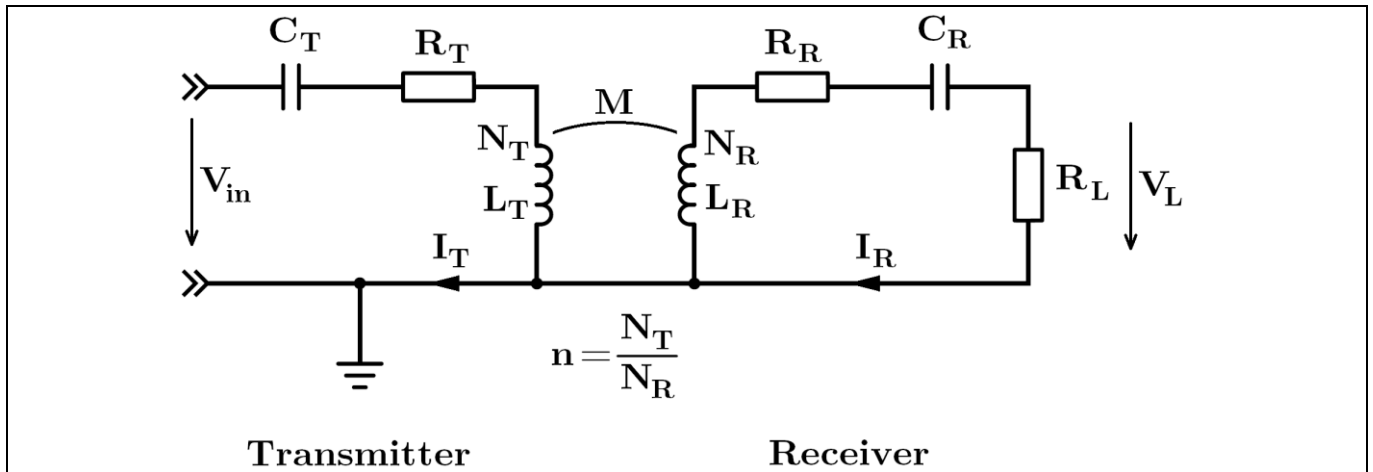


Figure 2 Wireless Power Transmission circuit with resonant coupled coils

If a receiver is placed in the field of the transmitter, it can take out some of the energy from the field of the transmitter coil. Without resonance, the part that does not pass through the receiver coil will not contribute to the WPT. Small distances between the transmitter and the receiver are typical for inductive non-resonant WPT schemes. These small distances result in a high coupling between the transmitter and the receiver where the coupling k is defined as:

$$k = \frac{M}{\sqrt{L_T L_R}} \quad (1)$$

When C_T and L_T are on resonance (at the operating frequency of 6.78 MHz), a strongly enhanced magnetic field will build up in the transmitter coil without a receiver because the magnetic field is increased by the resonance compared to the case without resonance. Due to the strongly enhanced resonant magnetic field in the transmitter coil, the receiver coils will be able to extract energy from the transmitter field at much bigger distances and at much lower coupling. However, the receiver cannot take out more energy than the transmitter puts in. Therefore, the maximum energy that can be extracted by the receiver is the input energy of the transmitter.

2 The math behind the principle

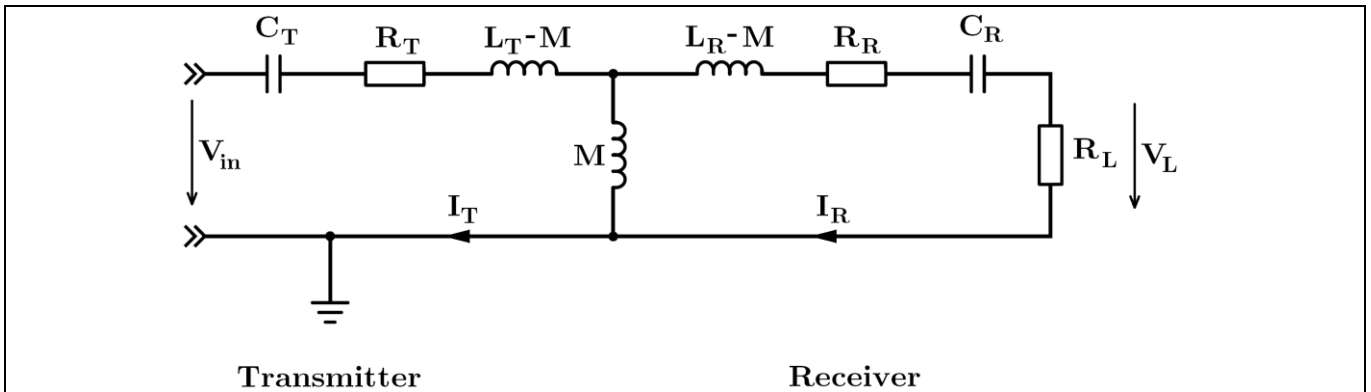


Figure 3 Equivalent of the WPT circuit with resonant coupled coils

The circuit shown in Figure 3 can be used to calculate the input impedance Z_{in} with the following formulas:

$$Z_{in}(\omega) = \frac{V_{in}}{I_T} = R_T + j \left(\omega(L_T - M) - \frac{1}{\omega C_T} \right) + Z_{parallel} \quad (2)$$

$$Z_{parallel} = \frac{Z_{serial} j\omega M}{Z_{serial} + j\omega M} \quad (3)$$

$$Z_{serial} = R_R + R_L + j \left(\omega(L_R - M) - \frac{1}{\omega C_R} \right) \quad (4)$$

On resonance $\omega = \omega_T = \omega_R$, where $\omega_T = \frac{1}{\sqrt{L_T C_T}}$ and $\omega_R = \frac{1}{\sqrt{L_R C_R}}$, the input impedance is ohmic and can be calculated with the formula:

$$R_{in}(k, R_L) = R_T + \frac{k^2 L_T}{C_R (R_R + R_L)} = R_T + \frac{\omega^2 M^2}{R_R + R_L} \quad (5)$$

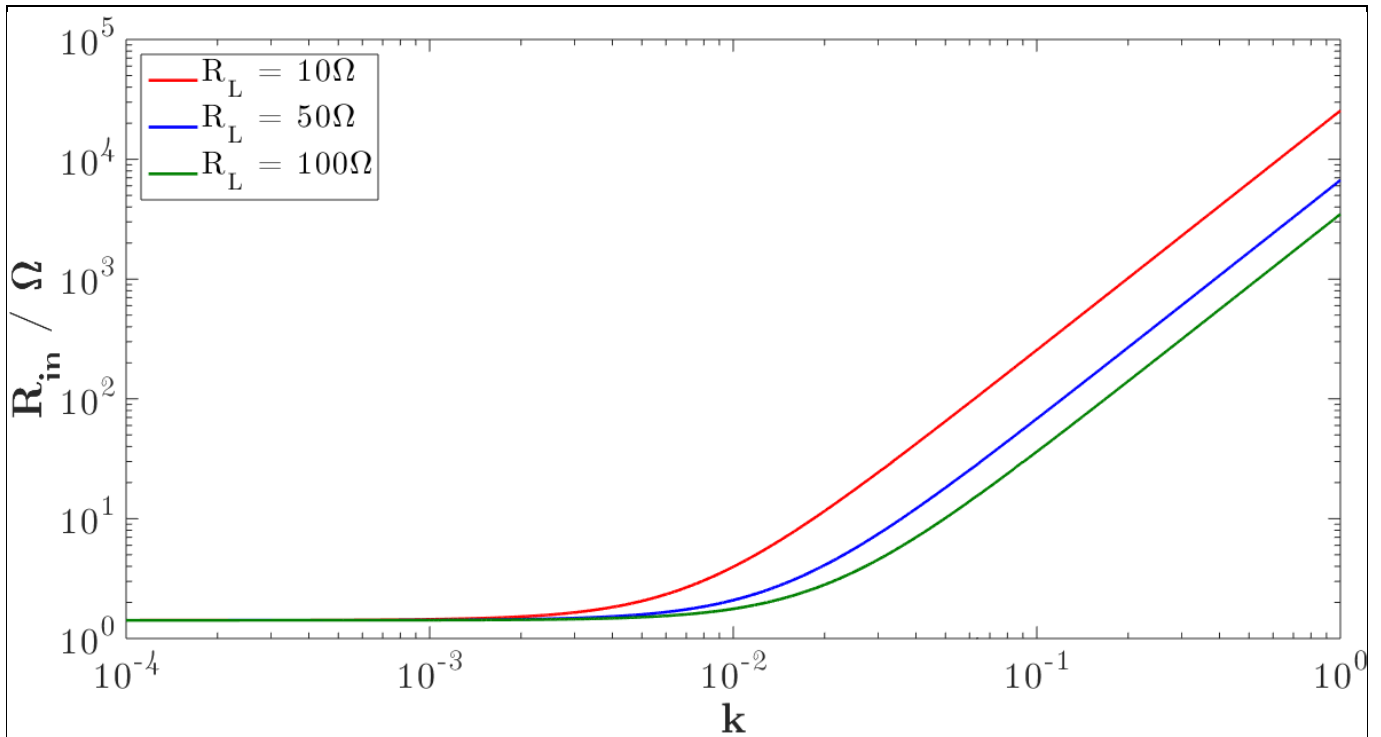


Figure 4 Input resistance R_{in} in dependence of the coupling k for various load resistances R_L with $L_T = 10 \mu\text{H}$ and $C_R = 27 \text{pF}$

On resonance, the receiver causes an additional load resistance that is seen by the transmitter. This is illustrated in Figure 5 and in the following formula:

$$R_{L,input}(k,R_L) = \frac{k^2 L_T}{C_R(R_R + R_L)} = \frac{\omega^2 M^2}{R_R + R_L} \tag{6}$$

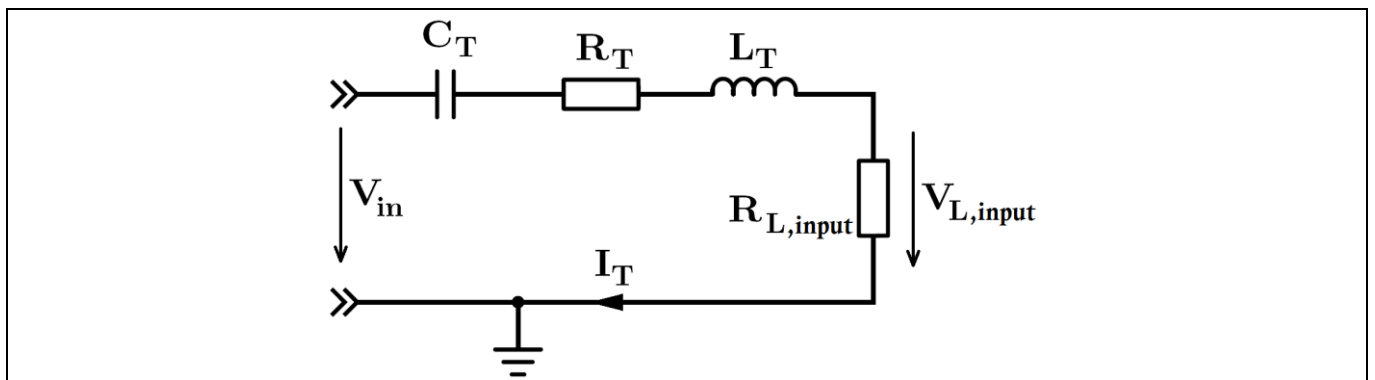


Figure 5 Circuit as seen by the transmitter (on resonance)

3 Coupling

Each transmitter has a maximum voltage of the amplifier and a maximum current which can be limited by the amplifier or the transmitter coil. In order to maximize the power at the receiver, the transmitter should be operated close to the maximum current and the maximum voltage. Therefore, there are three main cases for coupling: over-coupled, under-coupled and ideally coupled.

In the **over-coupled case**, the coupling is high and/or the load resistance R_L is low ($R_{L,input}$ is high). The receiver takes a lot of power out of the field of the transmitter coil. Thus, the resonance enhanced field cannot build up. The energy is consumed by the receiver and the input resistance (or impedance) of the transmitter will increase. The transmitter will be limited by the voltage of the amplifier.

In the **under-coupled case**, the coupling is low and/or the load resistance R_L is high ($R_{L,input}$ is low). A high field builds up in the transmitter coil but the receiver does not take out enough power for highest efficiency. The transmitter will be limited by the maximum current in the system.

In the **ideally coupled case**, the coupling k and the load resistance R_L are matched to one another such that the field in the transmitter coils builds up and the transmitter takes out the ideal amount of energy.

4 Quality factor

The voltage gain G_V is the ratio of the voltage at the load with respect to the voltage at the input.

$$G_V(\omega, k, R_L) = \frac{R_L}{Z_{\text{Serial}}} \frac{Z_{\text{parallel}}}{R_{\text{in}}} \quad (7)$$

The WPT efficiency η is defined as the ratio of the power that is dissipated in the load resistance over the power that is sent into the WPT system.

$$\eta(\omega, k, R_L) = \frac{\frac{|G_V V_{\text{in}}|^2}{R_L}}{\frac{|V_{\text{in}}|^2}{R_{\text{in}}}} = \left| \frac{R_L}{Z_{\text{Serial}}^2} \frac{Z_{\text{parallel}}^2}{R_{\text{in}}} \right| \quad (8)$$

The (unloaded) quality factor of the resonator is typically limited by the quality factor of the coil and can be described with $Q_T = \frac{\omega L_T}{R_T}$ and $Q_R = \frac{\omega L_R}{R_R}$ for the transmitter and the receiver. When supplying power to the load, the quality factor of both the transmitter and the receiver drops.

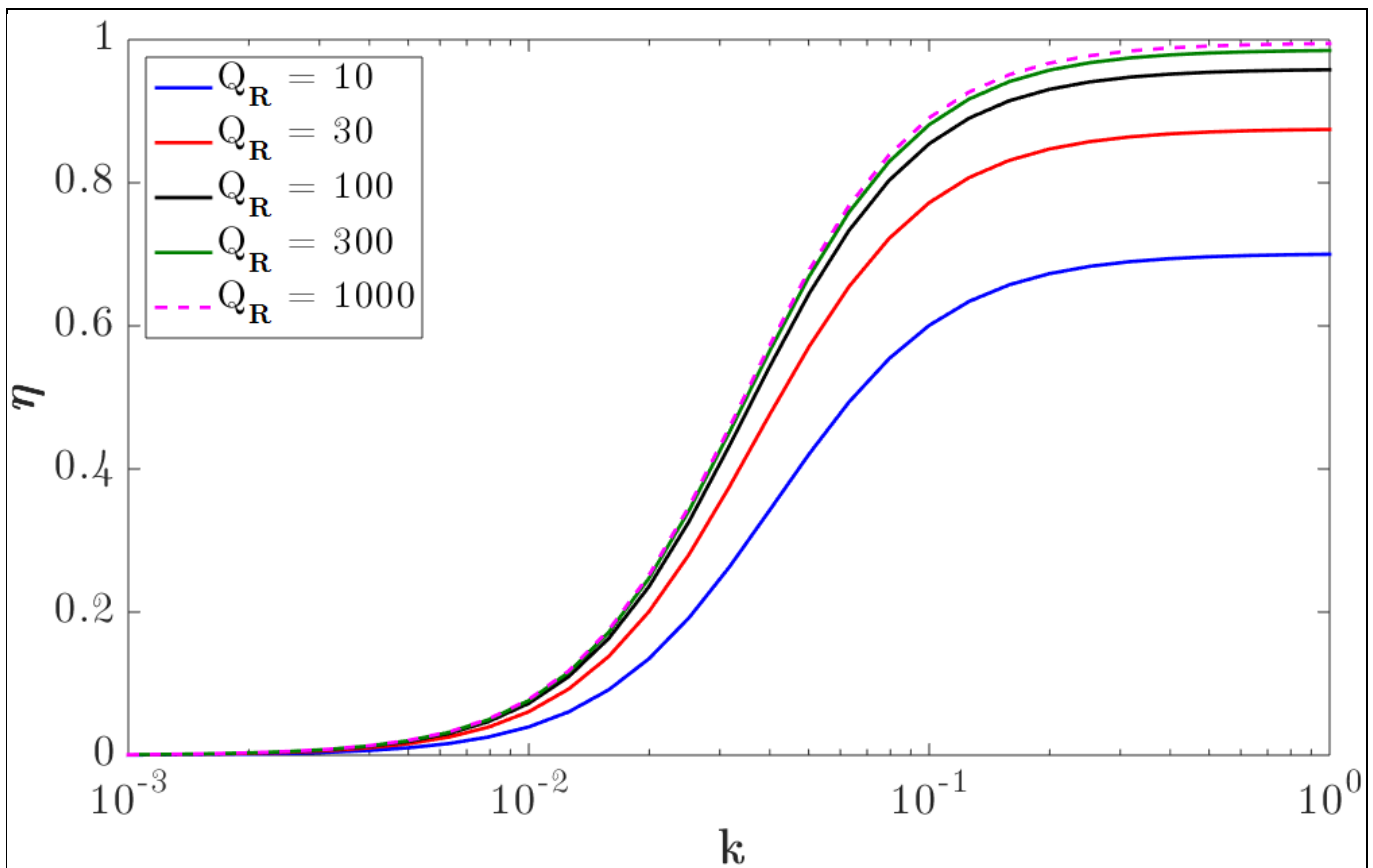


Figure 6 Efficiency as a function of the coupling for different quality factors of the receiver with $Q_{T, \text{unloaded}} = 200$, $L_T = 10\mu\text{H}$, $L_R = 5\mu\text{H}$, $R_L = 50\Omega$

Figure 6 shows the achievable efficiency in dependence of the coupling between the transmitter and the receiver for various unloaded quality factors of the receiver. On the receiver side, the voltage on the load will always be set by the ratio of R_L and R_R . Therefore, a high load resistance and/or a sufficiently high quality factor of the unloaded receiver of $Q > 100$ will allow high transmission efficiency.

For low coupling ($k < 10\%$), the voltage which is transmitted to the receiver is given by the voltage divider set by the two terms of equation (5). For weak coupling, the series resistance in the transmitter will absorb most of the power. With increasing coupling, the total input resistance will increase as well as the voltage available for transmission to the receiver. For strong coupling ($k \approx 1$), one can neglect the series resistance of the transmitter in input resistance with respect to $R_{L,input}$. Thus, the efficiency for $k \approx 1$ is mainly defined by the efficiency in the receiver.

Figure 7 shows the achievable efficiency in dependence of the coupling between the transmitter and the receiver for various unloaded quality factors of the transmitters. As expected, the maximally achievable efficiency ($k \approx 1$) is mainly defined by the efficiency in the receiver. A higher quality factor of the transmitter reduces the series' resistance and thus the input resistance. The higher the quality factor of the transmitter, the higher the efficiency is for low coupling ($k < 10\%$). This means that efficient WPT with big distances between transmitter and receiver, thus low coupling, requires a high quality factor of the transmitter coil.

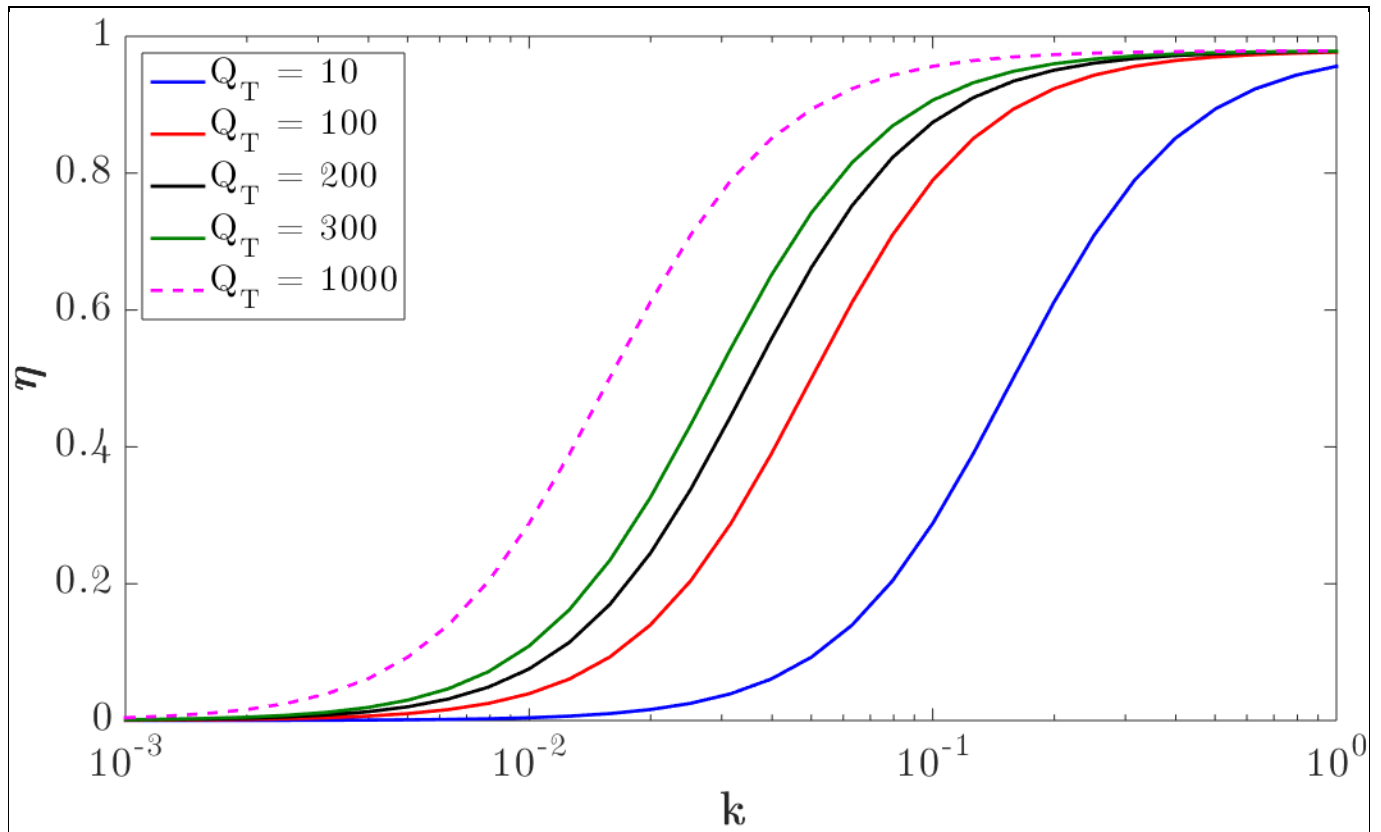


Figure 7 Efficiency as a function of the coupling for different quality factor of the transmitter with $Q_{R, unloaded} = 200$, $L_T = 10\mu\text{H}$, $L_R = 5\mu\text{H}$, $R_L = 50\Omega$

5 Conclusion

Current inductive wireless charging schemes work without wires, but the receiver, such as a smart phone, must be positioned very accurately on the charging pad for efficient power transfer. Resonant wireless charging will revolutionize wireless charging, because it is truly wireless. As long as the receiver is on the charging pad of a resonant wireless charger, the power transfer can be initiated efficiently.

For the design of a resonant wireless charging system, it is not sufficient just to understand the properties of the switches. An efficient design will require knowledge about the magnetic system as well. The operation principle and the math behind it are fundamental in understanding and designing a resonant wireless charging system. The result is a formula for the resistance seen by the transmitter on resonance which is used to estimate the maximum power that can be transmitted. It is a central part of the optimization process in the design phase of a wireless charging system. Furthermore, it is necessary to have a deeper understanding of the coupling between the transmitter and the receiver and the effects that the quality factors of the two coils have on the overall efficiency. A high quality factor in the receiver circuit will result in a high maximally achievable WPT efficiency. A high quality factor in the transmitter circuit will allow efficient WPT over larger distances.

References

[1] www.infineon.com

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