Inductive micro-tunnel for an efficient power transfer

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Abstract

Wireless powering allows the implementation of active implanted medical devices (AIMD) without batteries being inserted. The power is commonly transferred by an inductive link, which exhibits a strong relation between efficiency and coil configuration. For example, the electromagnetic coupling and consequently the transferable power rapidly decreases when the distance is larger than the biggest coil radius. To overcome this obstacle, we investigate an array of multiple equal small-sized electromagnetic resonators, which not only provides wireless power to a distant position with higher efficiencies, but also allows reducing the dimensions of the terminal coils.

Keywords: wireless power transfer; strongly coupled magnetic resonators; medical devices; electrical modelling

1. Introduction

For the treatment of common neuro-degenerative diseases, AIMDs [1,2] are used to perform measurements and generate electrical signals instead of conventional drug administration. Therefore, necessary powering systems typically employ inductive links with two loosely coupled coils. The efficiency of such a system is mainly related to the electromagnetic coupling, which requires large coils to minimize the attenuation due to the distance and consequently counter a further miniaturization.

Therefore, several applications exist, which use intermediate resonators [3-6]. The resonators serve as relay, providing the opportunity to transfer power to distant positions and to use smaller terminal coils. However, typical
biomedical applications do not apply more than four coils. Instead, intra-corporal cables are used, e.g., as part of the intermediate resonator [7]. The aim of our investigations is to avoid the mechanical problems generated due to the intra-corporal cables by replacing them with a sequence of resonators. As a consequence, the magnetic field is guided inside a defined channel similar to a tunnel. Existing drawbacks of power transfer technologies like electrical compliance or tissue absorption can be locally solved.

In contrast to previous resonator arrays [6,8,9], the presented work focuses on small-scale resonators with diameters of 1 cm at max. Instead of the typically used matrixes [9], the following section presents an analytical model based on a circuit of lumped parameters. This model is used to determine the reflected impedance, the optimal load, and an approximation of the resulting efficiency. The presented theory was verified in case of an initial prototype system, shown in section 3, and a final discussion allows the definition of requirements for a future system.

2. Theory

The proposed resonator array is modeled as a series connection of several loosely coupled transformers [10,11], which are tuned to a common resonance frequency. Under this consideration, all leakage inductances are compensated by the therefore used capacitor. The configuration forms a transmission line, in which each coil pair is represented by a T-section plus resistance as shown in figure 1.

![Fig. 1. Inductive tunnel modeled as transmission line](image)

The particular value of $R_i$ is therefore related to the quality factor of the resonator. It is assumed that these losses are dominated by the coil [12]. The other components, the T-section, are described via a fixed angular frequency $\omega$ and the mutual induction $M_i$, which is related to the magnetic coupling and consequently to the particular gap and the orientation of the resonator. Hence, a maximum in mutual inductance is reached in case of a coaxial alignment [10]. Moreover, the value of $M_i$ decreases by increasing the distances between the resonators, especially when the particular distance is larger than the coil radius.

The T-sections show a characteristic transfer behavior, which allows a determination of the reflected impedance $Z_i$. In each stage, the impedance is inverted and increased by additional losses from the resonator or respectively the load resistance $R_L$.

$$Z_i = R_i + \frac{\omega^2 M_i^2}{Z_{i+1}} \quad |_{i=N} \quad Z_N = R_N + R_L$$

Hence, the reflected input impedance of the configuration changes between high and low values, depending on an even or odd number of resonators. Under ideal conditions ($R_i \to 0$), this effect can be observed along the whole configuration. However, due to the losses, the constant inverting leads to a reflected impedance, which approximates the reactance generated by the mutual inductance. Using equal resonators and constant gap, further numerical computations on equation (1) exhibit that optimal efficiency is reached when a load equal to the mutual impedance ($\omega M$) is connected. In this case, the expected efficiency $\eta$ can be assumed as followed:

$$\eta = \left( \frac{1}{1+\frac{1}{R_L}} \right)^N$$

(2)
The equation shows that the efficiency of such a configuration therefore depends on the number of resonators $N$, the quality of the resonators $Q$, and the coupling factor $k$, which is directly proportional to the mutual inductance and consequently related to the gap between the resonators. For a given distance, it is therefore necessary to keep a balance between gap and number of resonators.

3. Implementation & Results

The multi resonator array based measurement setup was evaluated using a network analyzer with a configuration as shown in figure 2. This configuration applies up to 22 equal resonators placed in a distance of 5 mm with coaxial alignment. Each resonator consists out of ceramic capacitors and a two-layer circuit board coil with six turns and an outer diameter of 1 cm. The configuration is manually tuned to a common resonance frequency of 13.56 MHz and alternatively to 54.24 MHz for a small-scale setup. The corresponding quality factor is 68 for the lower and 100 for the higher frequency. The resonance frequency deviation between the resonators is below 0.5 % for both setups.

The initial measurement focused on the input impedances under open load condition. The configuration was therefore connected to one single port of the network analyzer ($S_{11}$ parameter). The result for the configuration, which is tuned to 13.56 MHz, is depicted in figure 3. The graph shows the expected input behavior, including the approximation of a constant input impedance value of 3.54 Ω, which corresponds to the particular mutual impedance ($\omega M$) plus a single resonator loss. Hence, the coupling factor between each coil pair is 9.2 %.

A second measurement is related to the efficiency. Therefore, a second resonator is used as port of the analyzer ($S_{22}$ measurement), allowing the determination of the corresponding optimum. The measurement readings are compared with theoretical values based on equation (2) as well as the impedances from previous measurement. A graphical representation is depicted in figure 4.
The graph shows a deviation between measured and estimated efficiency of 3.2 % at max. The measured efficiency is slightly reduced, possibly due to minimal mismatches or individual changes of the optimal load of the particular coil pair. Within the presented work, the developed micro tunnel is able to transfer 2.7 % of the transmitted energy over a distance of 14 cm using a coil diameter of 1 cm.

An additional investigation on the second setup shows a triplication in efficiency using 54.24 MHz. With further optimization of the resonator design, the efficiency can be significantly improved at higher frequencies, which will be presented in the future work.

4. Discussion

Figure 3 and 4 show the validity of the provided model and equations. The efficiency can be either improved by the configuration of the resonators or the resonator quality factors. Hence, the number of resonators as well as the particular gaps provide the opportunity to generate an optimum for a given distance and further investigations should focus on the implementation of the resonators.

The current implementation, which uses off-the-shelf circuit board technology, is almost on its limit. In particular, it is not possible to increase the number of turns due to the limited space and the typical design constrains, which significantly reduces the height of tracks on the inner layers.

Future version of this prototype system should consider on increasing the height of the tracks inside and outside the PCB resonator board and should employ frequency close to the upper operational limit, which is set by the corresponding skin effect.

5. Conclusion

Within this work, an array of up to 22 strongly coupled resonators is modeled and verified in case of an initial prototype. This initial prototype was able to transfer power over a distance of 14 cm using standard circuit board technology and a coil diameter of 1 cm. Two equations show the electrical behavior and determine the efficiency with a deviation below 3.2 %. Furthermore, the work suggests an optimization of the configuration (number of resonators vs. separation gap), resonator quality, and frequency to improve the efficiency in future systems.
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