Novel Highly-Efficient and Misalignment Insensitive Wireless Power Transfer Systems Utilizing Strongly Coupled Magnetic Resonance Principles

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Abstract

The wireless powering efficiency of traditional Strongly Coupled Magnetic Resonance (SCMR) systems is highly sensitive to the alignment between the transmitter and receiver elements; an issue that has limited their applicability in practical wireless power transfer systems. This paper proposes a novel set of SCMR-based topologies that are insensitive to misalignment and isotropic while providing large wireless powering efficiencies. The systems, which are presented here, achieve power transfer efficiencies above 50% over the complete misalignment range of 0−90° with performance that is significantly better than typical SCMR elements.

Introduction

Wireless **power** transfer methods have been utilized in the past for various applications. The Strongly Coupled Magnetic Resonance SCMR method is a highly efficient wireless power transfer technique that has been recently developed [1]. In order for SCMR to achieve high efficiency, it requires that the transmitting and receiving elements (typically loops or coils) are designed so that they resonate at the desired operating frequency that must coincide with the frequency where the elements naturally exhibit maximum Q-factor. A main disadvantage of conventional SCMR systems is that they are highly sensitive to the alignment between transmitter and receiver. An optimization technique for improving the efficiency of SCMR systems under lateral misalignment was presented in [2]. Specifically, 48.4% efficiency was achieved by using an adaptive matching network. However, no solution for angular misalignment was proposed in [2]. Analytical formulations for the power transfer efficiencies of inductive links under lateral and angular coil misalignment were presented in [3]. In addition, the effects of angular and lateral misalignment in inductively coupled systems, which simultaneously achieve WPT and data communication, were examined in [4]. Furthermore, analytical models for SCMR that incorporate misalignment effects were presented in [5].

SCMR's radial and angular misalignment sensitivity were examined by [6] and [7], respectively. Only [7], attempted to alleviate SCMR's angular misalignment sensitivity by using tuning circuits, which were not able to maintain high efficiency above 60° of misalignment. Also, it should be pointed out that tuning circuits add to the complexity of SCMR RX systems and cannot compensate for large angular and radial misalignments as they cannot recover the lost flux density between TX and RX. However, tuning circuits can be used for compensating the effects of variable axial distance between TX and RX [8], [9]. It can be seen that previous research efforts have investigated the effects of both lateral and angular misalignment of SCMR systems. However, no solutions, which are based on new geometries of SCMR elements, have been proposed to address the sensitivity of SCMR systems to lateral and angular misalignment. Also, no paper has attempted to design an SCMR system that exhibits isotropic wireless powering performance. This paper proposes a novel set of SCMR-based topologies that are insensitive to misalignment and isotropic while providing large wireless powering efficiencies. This type of system was first presented in [10]. The systems, which are presented here, achieve power transfer efficiencies above 50% over the complete misalignment range of 0−90° with performance that is significantly better than typical SCMR elements.

Standard SCMR

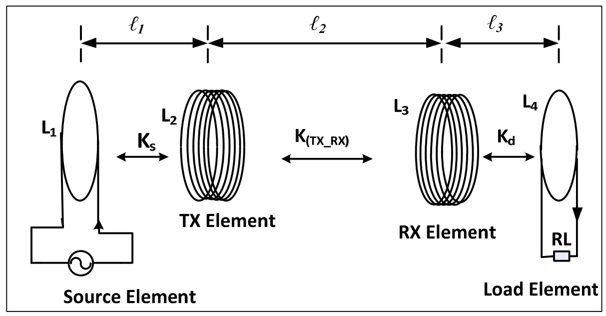


Figure 1. Standard SCMR System

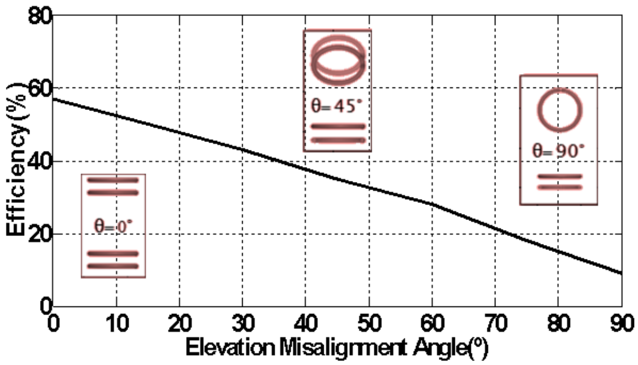
Standard SCMR systems consist of four elements (see Fig. 1) and require that TX and RX systems are aligned in order to achieve high efficiency. In fact, such standard SCMR systems suffer a significant decrease of their wireless powering efficiency when they are misaligned. This disadvantage greatly limits the application of standard SCMR systems since mobile, wearable or implantable, devices cannot be designed so that they are always aligned.

The main purpose of this paper is to provide a novel way to perform WPT that is misalignment insensitive. The following types of misalignment will be examined:

a. Angular azimuth misalignment - In this case, the RX system rotates around the Z axis from 0° to 90°, while the TX system is fixed.
b. Angular elevation misalignment - In this case, the RX system (RX resonator and load element) is rotated in the YZ (elevation) plane from 0° to 90° from the center between the two devices on their common axis, while the TX system (TX resonator and source element) is fixed.
c. Isotropy azimuth misalignment – In this case, we examine the performance when we rotate the RX system around the TX system by keeping its distance from TX system constant. Therefore the RX system moves along an azimuth sphere with a radius of the distance of these two.

d. Isotropy elevation misalignment – Much like previous case, we move the RX system along elevation sphere with a radius of the distance between RX and TX.

The performance of standard SCMR is examined here. All the simulations in this paper are performed in ANSYS HFSS and Designer. All load loops in the designs examined here are connected to 50 ohm loads. All SCMR resonators examined below were designed to resonate at the frequency where their Q-factor is maximum, which was accomplished using analytical equations for the standard loops and simulations for the proposed 3-D loops.



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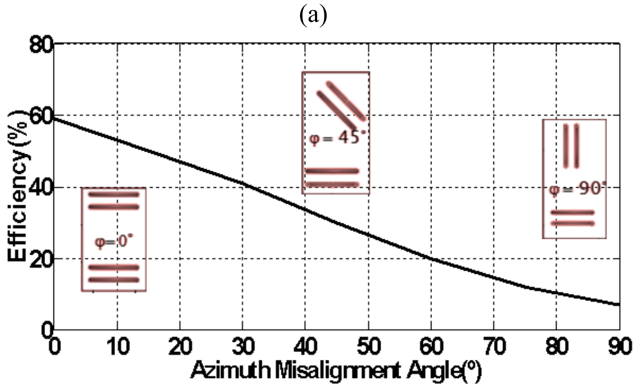

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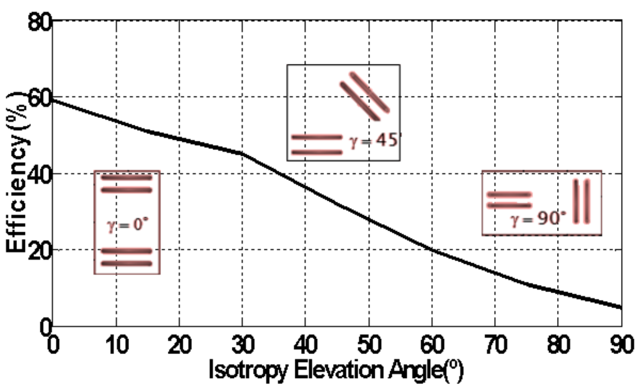


(c)

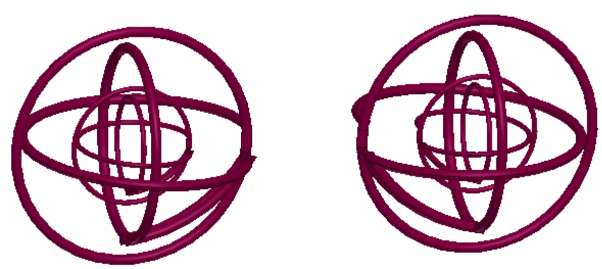
Figure 2. Standard SCMR under different misalignment conditions. (a) angular elevation, (b) angular azimuth, and (c) isotropy elevation.

The specifications of this SCMR system are as follows: the radius of the four loops is 50 mm, the thickness of the wire is 2.2 mm, the distance between RX and TX is 150 mm. A 78 pF capacitor is needed to achieve maximum efficiency, and the operating frequency is 40.8 MHz.

Fig. 2 shows the simulation results of the SCMR system for the different misalignment conditions. Specifically, Figs. 2(a) and 2(b) show the variation of SCMR's efficiency for elevation and angular misalignment conditions. The results clearly demonstrate the gradual decrease of efficiency and thus the high sensitivity of conventional SCMR systems to misalignment. Also, the isotropy of the SCMR system was examined in the elevation plane and the results are shown in Fig. 2(c). These results illustrate that the efficiency of the standard SCMR system does not exhibit isotropic performance in the elevation plane. Similarly, due to its geometric symmetry, this standard SCMR system does not exhibit isotropic WPT in the azimuth plane either.

Misalignment Insensitive SCMR System (3- loop structure)

In an effort to develop an SCMR system that is misalignment insensitive and isotropic, we designed the system shown in Fig. 3. The difference between this system and the standard SCMR is that each element (TX resonator, RX resonator, source and load) is a 3D loop that comprises of three continuous connected orthogonal loops. Due to its geometrical symmetry, this design is expected to provide misalignment insensitive performance. The 3-D RX and TX resonator loops are designed so that they exhibit their highest Q-factor at the frequency of operation and capacitors are connected at their feed point to resonate them at the operating frequency. The designs of this system are done using ANSYS HFSS simulation analysis and the specifications are discussed as follows.



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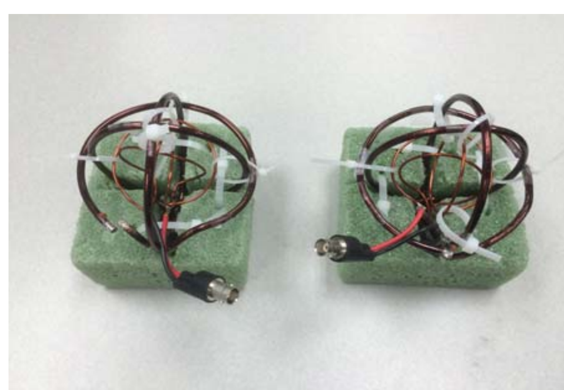
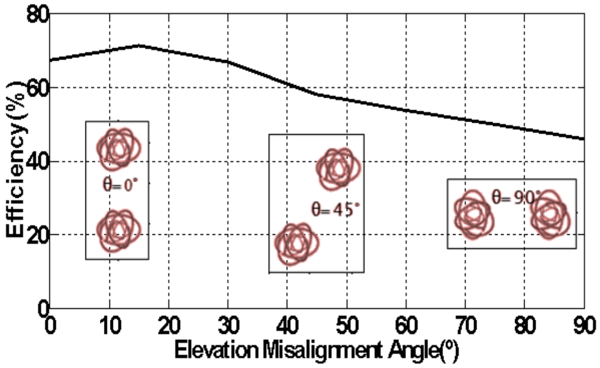
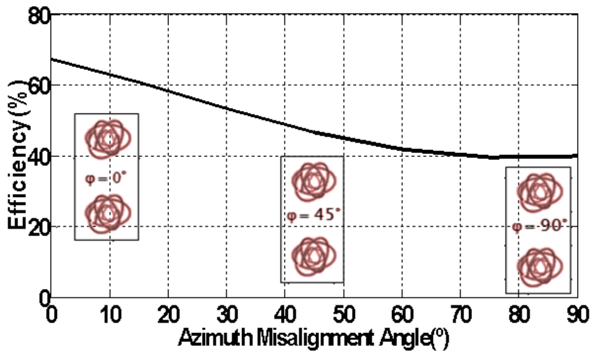


(b)

Figure 3. (a) Simulation Model, (b) Prototype



(a)



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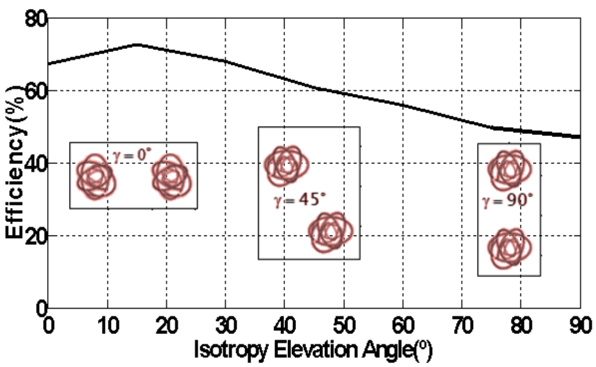

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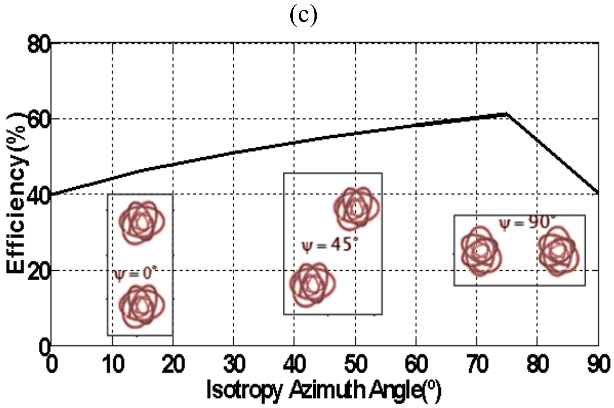
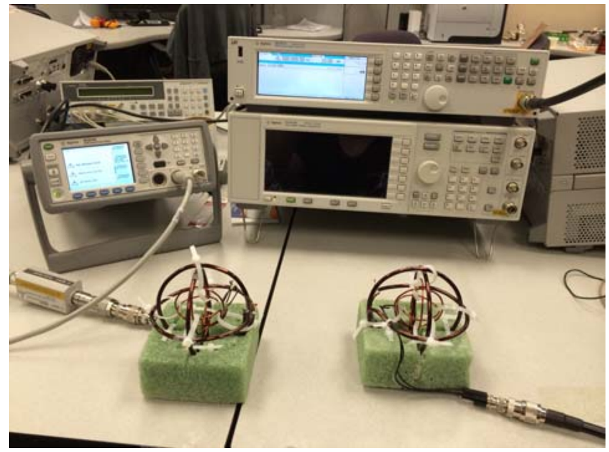


(d)

Figure 4. SCMR system of Fig. 3 under different misalignment conditions. (a) angular elevation, (b) angular azimuth, (c) isotropy elevation, and (d) isotropy azimuth.



(b)

Figure 5. Measurement setup.

The geometric specifications of the system, which is examined here, are described in what follows. The TX and RX resonators are comprised of three connected orthogonal loops with the following radii: the radius of the outermost loop is 50 mm, the radius of the inner loop is 45 mm, the radius of the innermost loop is 40 mm, and thickness of the wire is 2.2 mm. The load and source elements are comprised of three connected orthogonal loops with the following radii: the radius of the outermost loop is 25 mm, the radius of the inner loop is 22.5 mm, the radius of the innermost loop is 20 mm, and the thickness of the wire is 1.1 mm. The distance between the center of TX and RX systems is 150 mm. Each of the TX and RX resonators are connected to a 100 pF capacitor. This capacitance value was found by simulation analysis so that maximum WPT efficiency is achieved by the system. The operating frequency is 51.6 MHz.

Figs. 4(a) and 4(b) illustrate through simulation results that this system provides efficiency that is insensitive to angular (azimuth and elevation) misalignment. Also, Figs. 4(c) and 4(d) show that the system exhibits nearly isotropic wireless power transfer in both elevation and azimuth planes. The measurement setup is shown in Fig. 5

Conclusion

The paper proposed a novel SCMR system that exhibit misalignment-insensitive wireless power transfer. The system uses 3-D elements (source, load, TX and RX resonators) comprising of three continuous and connected orthogonal loops. Also, in this system the source and load elements are concentrically embedded into the TX and RX resonators, respectively. This system achieves power transfer efficiencies above 50% over the complete misalignment range of 0 - 90° with performance dramatically better than typical SCMR elements that are highly sensitive to misalignment. Also, this system is the first WPT system that exhibits isotropic performance in both elevation and azimuth planes thereby providing an efficiency that only depends on the distance between the TX and RX subsystems. The misalignment insensitive and isotropic performance of the proposed SCMR system is due to its geometrical spherical symmetry.

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