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A RECONFIGURABLE ANTENNA FOR ENHANCING THE MAGNETIC COUPLING IN WPT

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Abstract – IPT (Inductive Power Transfer) is an approach based on magnetic coupling to realize a wireless power transfer (WPT) system. In applications using IPT as a mean for transferring power, like RFID, it is of great interest to have a free positioning system, meaning with fewer constraints on relative positioning and orientation between the sender and the receiver. One of the problems which face the free positioning WPT by using IPT is the great sensitivity of the system to lateral and orientational misalignment between the sender and the receiver of power. This could hugely reduce the efficiency of the whole system for certain lateral and orientational misalignments, resulting in null points for the coupling coefficient, therefore no power transfer or no detection in case of RFID. In this work, we propose a reconfigurable antenna which changes its structure by turning on and off specific parts of itself. This will guarantee the effective power transfer in the range of interest, regardless of the lateral and orientational misalignments between the sender and the receiver. The same system can be used to increase the RFID read range by steering the magnetic field in certain direction. In general, the steering of the magnetic field could be used to achieve more efficient power transfer.

Keywords— Wireless power transfer, free position WPT, Beamforming, twisted loop antenna, configurable antenna, magnetic coupling, RFID.

I. INTRODUCTION

One of the most promising WPT in the near field is IPT. In Inductive Power Transfer one of the parameters mainly affecting the efficiency of power transfer is the mutual inductance. Due to the vectorial nature of the magnetic field,

mutual inductance depends strongly on the relative position and the orientation (angle) between the sender and the receiver coils. For certain positions and orientations there can be essentially zero coupling. Those are null areas. If the receiver is in null area, due to very low mutual inductance there would be no power transfer between the sender and the receiver which is a problem. For example, in the case of

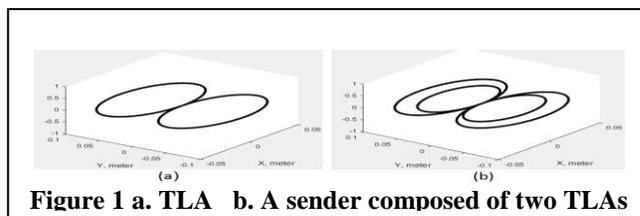


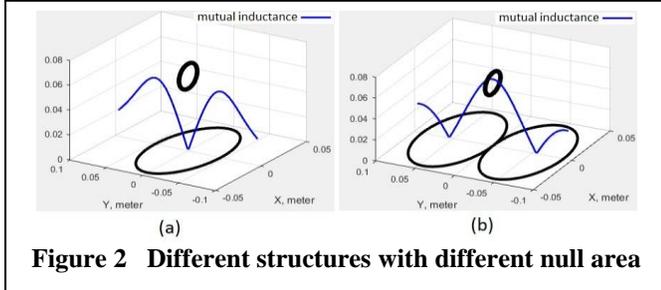
Figure 1 a. TLA b. A sender composed of two TLAs

RFID systems, the tag will not be detected. In previous works, one of the proposed solutions was the use of a Twisted Loop Antenna (TLA) instead of a traditional simple circular coil as a sender of power [1]. Fig. 1a shows such a TLA. Though in [1] TLA was consisting of one turn loop on each side with the electrical current flowing in one direction in one loop and in the opposite direction in the other loop, alternative options are possible. The TLA can have a different number of turns in each side with current flowing in any direction. Furthermore, it can be more complex as in Fig 1b where we have a structure consisting of two co-centered and co-planar TLAs. The measurements based on the idea of using TLAs as a sender showed an enhancement of the performance of the system in terms of reducing the null areas

[2, 3]. But we should remind that though this structure reduces the null area it does not completely eliminate them and optimization is still required.

II. RECONFIGURABLE ANTENNA

In this work, we try to build upon the idea of using TLA for Inductive Power Transfer. Our interest is related to small



receiver coil relative to the size of the sender. In our study, the sender consists of two TLA: A small TLA and a large TLA, the small one is placed inside the large one. The diameter of each coil of the large TLA is 8 cm which makes the total length of the sender 16 cm. The diameter of the receiver coil is 1 cm. Those diameters are chosen because they are realistic.

This study follows a step by step reasoning:

1. Any sender structure will have some null areas. It is impossible to have a structure with no nulls for all possible orientations of the receiver, because it is always possible to have the receiver coil parallel to the field which will give us a null mutual inductance, in other word eliminating all null area is not possible for a fixed sender structure.
2. Those null areas are unique to each structure. For example, if we are using a simple coil as a sender centered in the origin and the receiver coil has perpendicular orientation and is placed above the origin, as in Fig.2 a, the receiver is in null area. If we replace the sender coil with a TLA, as in Fig. 2b, the receiver coil is not any more in a null area in regard to TLA.
3. Having more than one sender structure at the same time is not a solution to eliminate these null areas, because the whole

set of senders could be regarded as one sender structure with its own null area and it will bring us back to the point one. This is still a fixed structure antenna.

4. Sweeping through a set of different sender structures, one by one, at each time step, could eliminate the null area if this set of sender structures are chosen correctly. This is our choice, and considered as a reconfigurable structure antenna.

5. As an electronically reconfigurable structure we propose a sender composed of several co-centered and coplanar TLAs. We have chosen only two TLAs here just for the sake of demonstration, but in a practical system the number of TLAs depends on the volume we want to cover.

6. To configure the structure, we can modify: (1). The radius of TLAs. (2). The number of turns in each side of TLAs. (3). the direction of current.

7. Electrically controlled hard switches enables us to dynamically control the number of turns in each side of TLAs and the direction of current in them, the radius of TLAs is not electrically controllable.

To find the number of required structures, which is also the number of required steps, the volume of interest is divided into cells, say cell-1, cell-2, etc. The number of cells depends on the volume to be covered, the size of sender, the minimum required mutual inductance between sender and the receiver, etc. In the first step, TLAs create a magnetic field which would give an acceptable mutual inductance if the receiver coil was in cell-1 and in horizontal XY plane. In the second step TLAs create a magnetic field which would give an acceptable mutual inductance if the receiver coil was in cell-1 and in one vertical XZ plane, and in the third step TLAs create a magnetic field which would give an acceptable mutual inductance if the receiver coil was in cell-1 and in second vertical YZ plane, hence we insure that regardless of the orientation of receiver coil if it is in the cell-1, it will have good mutual inductance at least in one step. Then the same procedure is repeated for all other cells.

Finding out the structure of TLAs that will give a suitable magnetic field for each step, is to find out the number of turns in each side of the TLAs and the direction of the current in them. Then by switching on and off some turns of the TLAs, we will have different structure in each step, which in its turn give rise to different magnetic field orientations in each step.

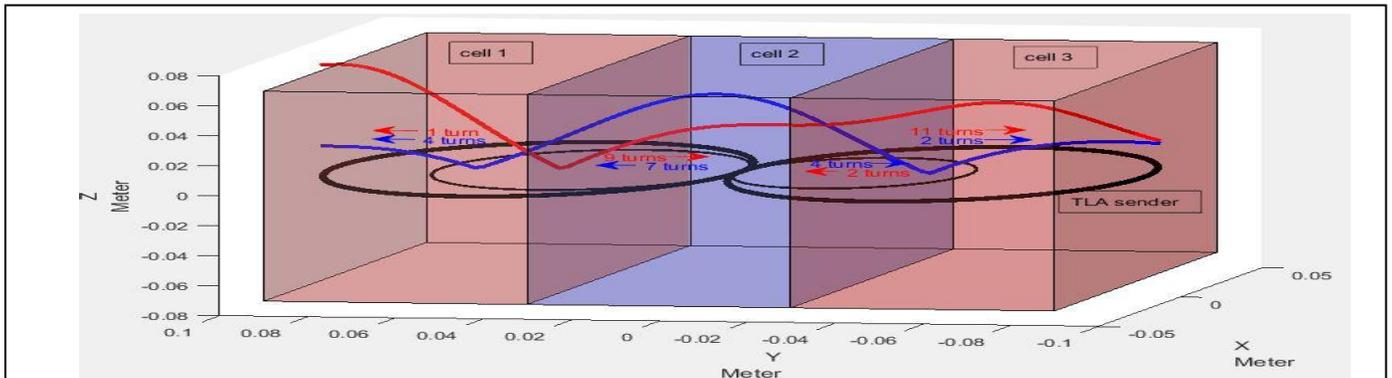


Figure 3 Proposed solution: Dividing the volume of interest into cells. Red curve covers cell 1 and 3, those are the red cells, and the blue curve covers cell 2, this is the blue cell.

This information about the required structure for each step and how to change the number of turns and the direction of current in them, can be stored in a microcontroller to repeatedly run through them one by one and in doing so we cover all the volume of interest for all the possible orientation.

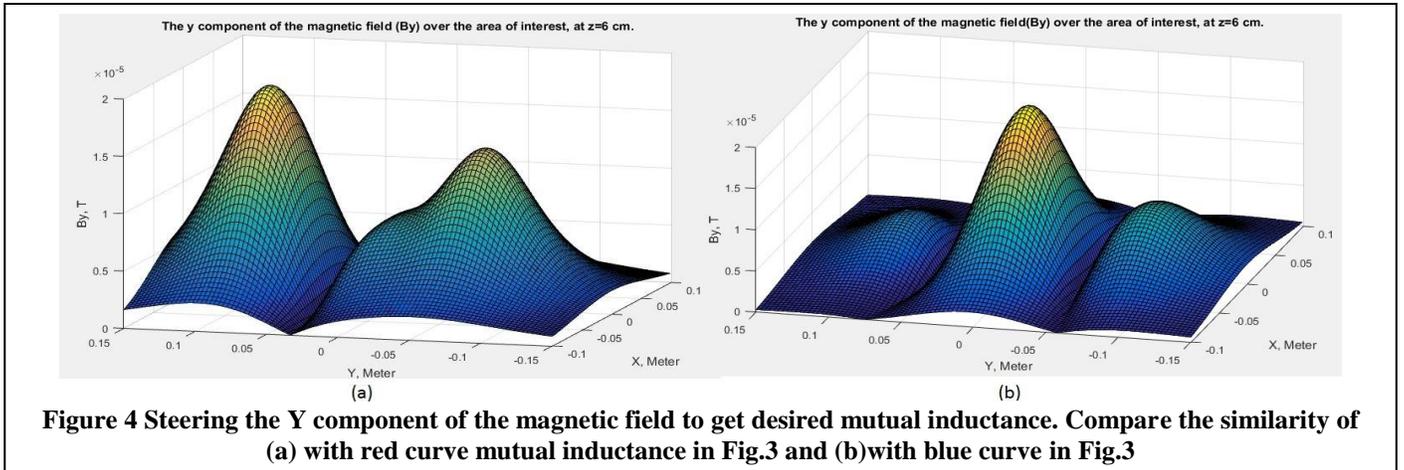
III. SIMULATION RESULTS

Our goal is to deduce the structure needed for producing the desired magnetic field in each step. Therefore, we need first to calculate the magnetic field of a TLA in general. The TLA is a set of current carrying loops and the magnetic field of a TLA is the superposition of fields due to each loop. For calculating the magnetic field of a loop, first the magnetic vector potential of one loop is calculated, then its curl is calculated to get the magnetic field. We followed an approach similar to the approach in [7, 8, 9] with extensive use of Mathematica and MATLAB software packages. It should be mentioned that we calculated magneto static fields due to constant current. If the signal wavelength that drive the antenna is large in respect to the antenna length, we could assume we have a quasi-static magnetic field which is approximated very well by the calculated static field. For this reason, the measurement will be done at low frequencies (from 100 kHz to 15 MHz). These values cover the HF RFID with operating frequency of 13.56 MHz, which is one of the possible applications of our method. In this work the volume of interest is divided into just three cells as is shown in Fig.3. and we cover just one orientation of the circular receiver coil, namely the receiver coil being in XZ plane. Of course, it is a very crude system, but the point is to show the applicability of the system rather than building a complete realistic system. The volume of interest spans for 20 cm in the Y direction, centered at the origin, 12 cm in the Z direction, and 12 cm along X axis. We want our system guarantees that inside the volume of interest there is no null area, and furthermore regardless of the position of receiver coil, the mutual inductance of sender and receiver is at least 3 nH, here we choose this value depending on the minimum requirement of our experimental tools, for other systems this value is calculated depending on the minimum power required to be transferred to the receiver [6]. We divide the range of interest into three cells, one cell from -10cm to -2 cm, second from -2

cm to 4 cm, and the third from 4 cm to 10 cm, all in Y axis. The number of cells depends mainly on the volume to be covered and the minimum mutual inductance required, as we mentioned earlier. However, sometimes it's possible to cover more than one cell by just one excitation, though this might result in having little area with mutual inductance less than required mutual inductance, which is in our case 3nH. From desired field for each step, we deduce the required structure that will produce that desired field. The simulated results are shown in Fig. 3. The arrows next to each loop show the number of turns and the direction of the current in that loop of TLAs. If the sender structure is what is indicated by the red arrows, we would have the mutual inductances shown by the red curve, suitable for covering cell-1 and cell-3 ie. the red cells. If the sender structure is what is indicated by the blue arrows, we would have the mutual inductances shown by the blue curve, suitable for covering cell-2 ie. the blue cell. Here we can see that one excitation covers the cell 2, and another excitation covers both cells 1 and 3. There is a small area with mutual inductance less than aimed 3 nH in cell-3 but it's just a result of covering three cells by two structures, and could be easily solved by increasing the number of cells. We observe that different configurations lead to a magnetic field profile specific to each configuration. If the receiver coil is in XZ plane, only the Y component of the field contributes to the mutual inductance between sender and receiver, hence by controlling the Y component of the field, the mutual inductance can be controlled and steered in a desired way. Fig. 4 shows the Y component of the magnetic fields of the two structures of Fig. 3. It clearly shows that the mutual inductance in Fig.3 is just a consequence of this field steering.

IV. MEASUREMENT

In the measurements part of this work we switched the structure from the first configuration to the second configuration manually. Although designing a switching circuit is a straightforward task, it will be done later while initial experimental results were needed fast for method assessment. For measuring the mutual inductances between the sender and a vertical coil, we move the receiver along all the region of interest step by step, while keeping it in a same vertical orientation. At each different position, we measure the



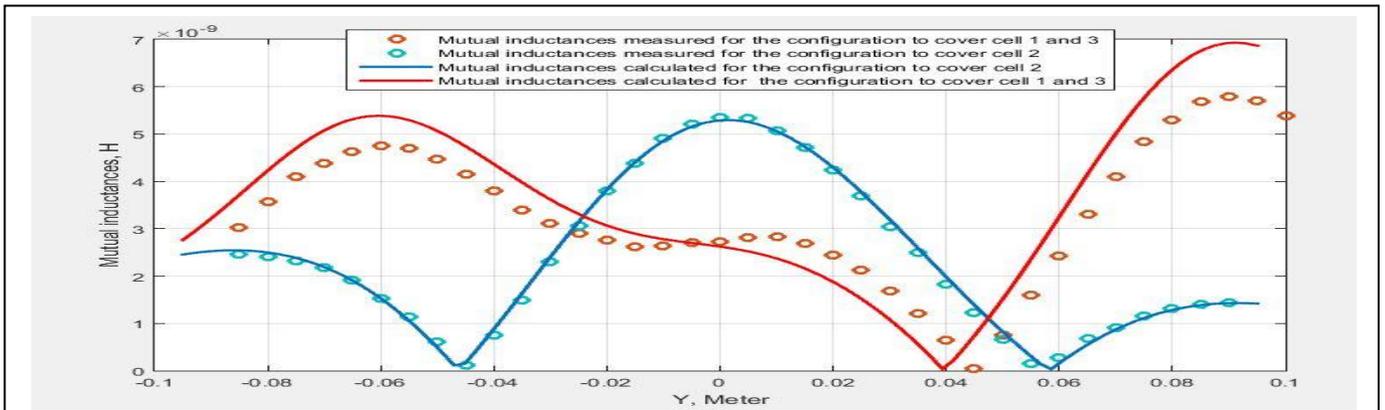


Figure 6 Comparison between calculated data and measured data for two different structures (mentioned in Fig. 3)

mutual inductance between sender and receiver using a ROHDE & SCHWARZ ZNB 8 Vector Network Analyzer. The length of the TLAs is 18 cm, the diameter of the receiver coil is 1 cm, and we do the measurement when the receiver is located at the limit of the area of interest, above the antenna at a distance of 6 cm, as shown on Fig. 5. Fig. 6 shows the results at 100 kHz. These values are obtained in the upper boundary of the volume of interest, with the $z=6$ cm. For the lower boundary at $z=-6$ cm, because of symmetry we will have the same results. We do the measurement in the boundary of the cell, because the mutual inductance become smaller as the distance from sender increases, so the lowest value of mutual inductance in a cell, is at its boundary. If we guarantee the mutual inductance in the boundary of the cell is more than 3nH, we could be sure it is also higher than 3nH everywhere in that cell. It also should be mentioned that we don't consider the maximum mutual inductance here, because of the small size of the receiver coil, even with maximum possible mutual inductance, the coupling coefficient remains small and it probably will not cause the problem of strong coupling and frequency shift, nevertheless, this should be verified in continuation of this preliminary work. The red curve shows the mutual inductance due to the first structure of the TLAs, which covers the cell 1 and cell 3, and the blue curve is the mutual inductance due to the second structure of the TLAs, which covers the cell 2. For the first case, we have an average difference between calculated and measured values of 13%, and for the second case, it is 1%. The better agreement between measured results and calculated values for second structure in comparison to the first structure are probably due to second structure being better fabricated in term of better resemblance with the simulated structure. Table 1 shows the values of self-inductance of each structure.

Table 1

Structure (covering cell)	Self-inductances
First structure (1, 3)	24.0 μ H
Second structure (2)	15.0 μ H

V. CONCLUSION

The TLAs could be considered as an array of coils and different structures create different excitations. This method is very well known for far-field radiation. However, we

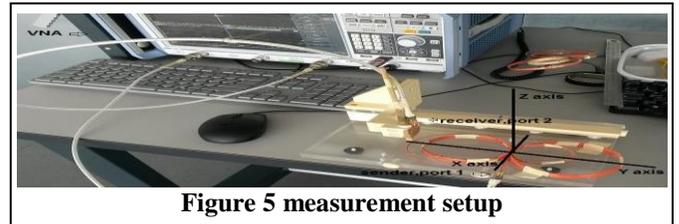


Figure 5 measurement setup

applied it here to near-fields. The same method could be used to increase the range of wireless power transfer. The idea of using array-like structure to increase the efficiency of power transfer was proposed in [4, 5]. However, we here followed a new approach and proposed an application of this principle, namely a system which guarantees power transfer regardless of misalignment between sender and receiver. The measurement showed agreement between calculation and the measured values for the mutual inductances, which confirms the feasibility of the method. This system could be more developed to obtain the ability to localize the position of the receiver coil by monitoring how the input impedance of the sender changes in each step.

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