

Specialized receiver for three-phase contactless energy transfer desktop applications

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Specialized Receivers for Three-Phase Contactless Energy Transfer Desktop Applications

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Keywords

«Distribution of electrical energy», «Magnetic device»

Abstract

In this paper, a new contactless energy transfer (CET) desktop application is presented. The CET desktop uses a matrix of hexagon spiral windings embedded underneath its surface, to transfer power to CET enabled consumer electronics devices placed on the table. To improve efficiency and limit stray magnetic fields, clusters of only three primary coils, located closest to the receiving devices, are excited. The coils are excited with out-of-phase currents to further reduce stray magnetic fields. Due to the design of the CET desktop the power transfer efficiency is not constant but varies throughout the surface of the table. Using the design and evaluation process presented in this paper, different secondary coil configurations can be designed and evaluated to find topologies best suited for different electronic devices. The evaluation process is simulated for two different receiver coil assemblies, and from the results it is shown that receiver coil configurations with multiple small coils have the ability to stabilize the power transfer efficiency in the CET desktop.

Introduction

Contactless Energy Transfer (CET) is the process in which electrical energy is transmitted between two or more electrical devices through inductive coupling as opposed to energy transferred through conventional “plug-and-socket” connectors [1]. CET desktop applications and other similar CET charging platforms are realizations of this concept where a table or a platform embedded with “power transmitting” coils, have the ability to power or recharge different consumer electronic devices, such as cellular phones, portable music- and multimedia players and laptops, fitted with “power receiving” coils, by simply placing the devices on top of the desk or platform (Fig. 1). This technology does not only make the devices more user friendly by removing the need for cables and power adaptors, but also more appealing to buyers in the ever increasing and demanding consumer electronics market, where electronic manufacturing companies constantly seek new and innovative technologies to give their products advantages over that of their concurrents.

Currently, many papers exist on the topic of CET, where the authors discuss ways of transferring power between single pairs of circular windings [4] or between multiple primary and secondary winding arrays [2], [3] for a wide range of different applications.

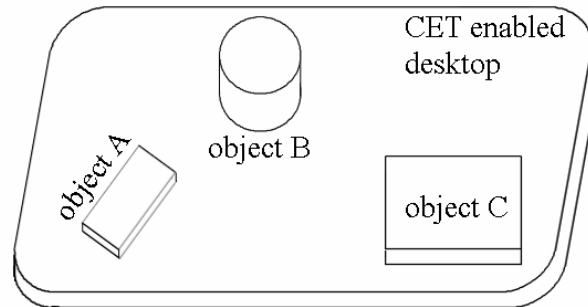


Fig. 1: CET receiver objects randomly placed on a CET enabled desktop for charging.

Presented in [4] is a CET cellular phone battery charger which uses a pair of low profile circular printed circuit board (PCB) windings to transfer energy from a desktop unit to a phone. The coil implanted in the phone is placed in parallel, with perfect overlap directly above the primary coil for maximum electromagnetic coupling and energy transfer. The results show reasonable power transfer efficiency of 57 % over the 2.4 mm air gap, but due to the use of only single primary and secondary coils it does not have the ability to deal with large lateral displacements between the coils.

Proposed in [2] is a contactless battery charging platform which incorporates three layers of hexagon spiral winding arrays. The three layers are specially positioned relative to each other, to create a uniform magnetic field density above the platform. Receiver coils placed above and in parallel with the charging platform experience an unvarying induced voltage and a stable power transfer even with relative movement in the plane. One major drawback of this system is that all the primary coils, in all three layers, should be continuously energized to produce the resultant uniform field, even when no receiving devices are in range. Currents circulating in the coils constantly dissipate power due to their resistances, which could result in a major reduction in power transfer efficiency, as well as increase in temperature and possible overheating of the primary coils. For applications where the transfer of power could possibly be in the hundreds of Watts, high power transfer efficiencies and low operating temperatures are essential for guaranteeing stable operations. Furthermore, since all the coils are constantly energized, they continuously radiate magnetic fields into the surrounding air. These stray magnetic fields could undesirably couple with other electronic devices in the vicinity possibly causing them damage or interfering with their normal operations. It is also possible that large radiated magnetic fields not complying with the regulations set out by the regulatory authorities could be dangerous or harmful to humans.

In this paper, a new CET desktop application is presented. Similarly to [3] and [4] it utilizes a matrix of hexagon spiral windings embedded underneath the surface of a table. The main purpose of which is to power and/or recharge electronic devices placed thereupon. What makes this system different from [3] and [4] is that it attempts to increase power transfer efficiency and reduce stray magnetic fields by energizing only a small cluster of three primary coils located closest to each receiving device placed on the table. The magnetic field is thus localized to only certain specific positions around the table. Additionally, the magnetic field is further reduced by employing the magnetic field shaping technology presented in [1]. By exciting each cluster of three primary coils with out-of-phase currents, the magnetic field is concentrated around the primary coils, and the field further away is strongly attenuated due to the destructive interference of the individual fields.

Unfortunately, inherent to the design of the CET desktop application are “dead spots” or areas on the table where no transfer of energy occurs. Receiver devices placed at different locations on the table will not experience the same power transfer efficiency and at some positions, possibly no power transfer of at all. Special receiver coil configurations are thus needed to stabilize the power transfer across the desk. The problem addressed in this paper, is that of designing and evaluating different receiver coil configurations to find a topology which is best suited for the CET desktop application and will give a stable and position insensitive transfer of energy by using complex receiving coil arrangements in the receiving devices.

The process of designing and evaluating a receiver coil configuration starts by noting that contrary to the large single receiver coils used in [3], only a combination of multiple smaller receiver coils will suffice for transferring power over the CET link and at the same time stabilize the position sensitivity thereof. The design of receiver coil configurations is an iterative process where the dimensions and characteristics of the individual receiver coils are modified and evaluated until they meet the specific power and size requirements for the individual electronic devices. The evaluation process calculates the maximum apparent power transfer efficiency between the transmitting and receiving coil clusters for a wide range of relative cluster positions. This results in a three-dimensional graph, called an efficiency-position graph, which shows the locations and the severity of the “dead spots”. Different receiver coil assemblies can then be evaluated by comparing these graphs against each other. A graph showing multiple “hills” and “valleys” are more position sensitive in terms of their power transfer efficiency than graphs with a flatter landscape. The aim is to find a receiver coil arrangement with the least amount of variance in its efficiency-position graph.

The developed evaluation method is demonstrated in this paper by simulating two separate receiver topologies. The first receiver consists of a single hexagon spiral winding. The simulation results show a “dead spot” in the center of the primary coil cluster which illustrates the need for more complex receiver coil configurations to stabilize the power transfer. In the second simulation, a seven-hexagon spiral winding topology is evaluated. The simulation results show less variance in the efficiency-position graph with multiple small peaks and valleys but no “dead spots”. Although this receiver assembly is better suited for the CET desktop than the receiver presented in the first set of simulations, it might still not be optimal. Through the use of the techniques presented in this paper it is possible to evaluate different receiver configurations, and through comparison, find the receiver coil topologies best suited for the different electronic CET devices.

Contactless energy transfer desktop

The main method through which energy is transferred between the CET desktop and the electrical devices placed thereupon is by magnetic fields and the mutual inductance between their primary and secondary coils. The system operates in the magneto-static domain where the electrical field and electrostatic charges are ignored. The efficiency of the energy transfer is thus primarily dependent on the coils used to generate the magnetic fields. The hexagon spiral windings (Fig. 2(a)) proposed in [2] have unique characteristics that make them exceptionally well suited for use in the CET desktop application. Firstly, they can easily be produced as copper tracks on thin PCB substrates, and due to their low profile, easily be embedded into different devices, device casings or table surfaces. Secondly, because of their particular shape, they produce a triangularly shaped magnetic field density with a strong z-component, perpendicularly above them, as shown in Fig. 2(c). Secondary coils placed in parallel directly above them will thus experience a strong electromagnetic coupling, and increased power transfer efficiency. In a typical CET desktop application, an electrical device, like a cellular phone or laptop, will have the secondary coils embedded into their casings. When these devices are lying on the table, the primary and secondary coils will automatically be positioned parallel to each other, separated by mere millimeters. For the sake of simplicity, a hexagon spiral winding will be represented as a plain hexagon as depicted in Fig. 2(b).

In the CET desktop application a wooden or plastic table is embedded with a matrix of hexagon spiral windings just a few millimeters (typically 1 – 2 mm) below its surface (Fig. 3(b)). Incorporating the magnetic field shaping technology presented in [1], the primary coils are arranged so that adjacent coils are excited with out-of-phase current waveforms. As shown in Fig. 3(a), the coils labeled “A” are excited by a current with a 0° phase angle, the coils labeled “B” are excited with a 120° current phase angle and the coils labeled “C” with a 240° current phase angle.

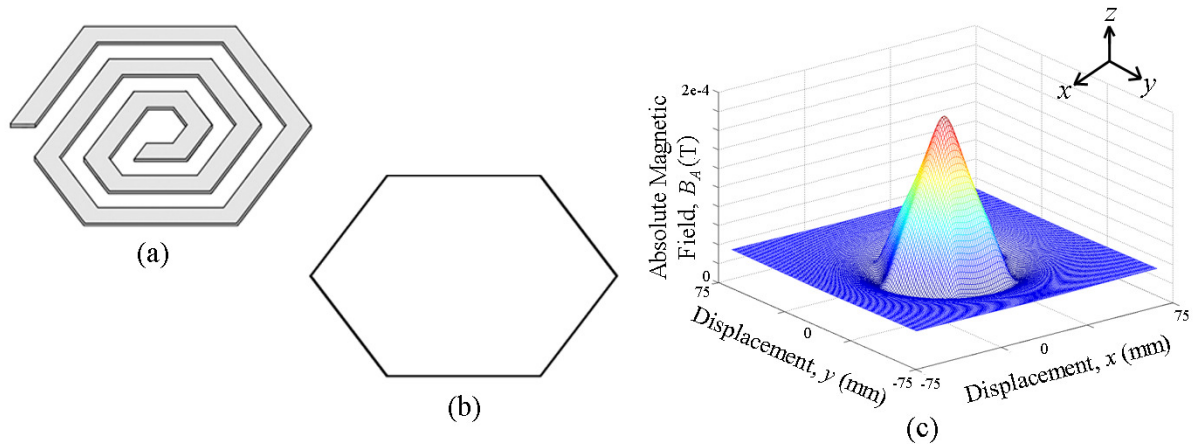


Fig. 2: (a) A hexagon spiral winding, (b) a simplified representation of the hexagon spiral winding, and (c) the absolute magnetic field distribution produced by a hexagon spiral winding with a 40 mm radius calculated using [5] at a height of 5 mm above the coil.

To remain magneto-static, the switching frequencies are generally limited between 100 – 400 kHz (150 kHz typically). When CET enabled electronic devices are placed on the table, a cluster of three primary out-of-phase excited coils, located closest to the receiving device, are activated to the transfer power (Fig. 3(b)). For the purpose of this paper, the power electronics and controlling circuitry used to drive and switch the individual coils will not be discussed.

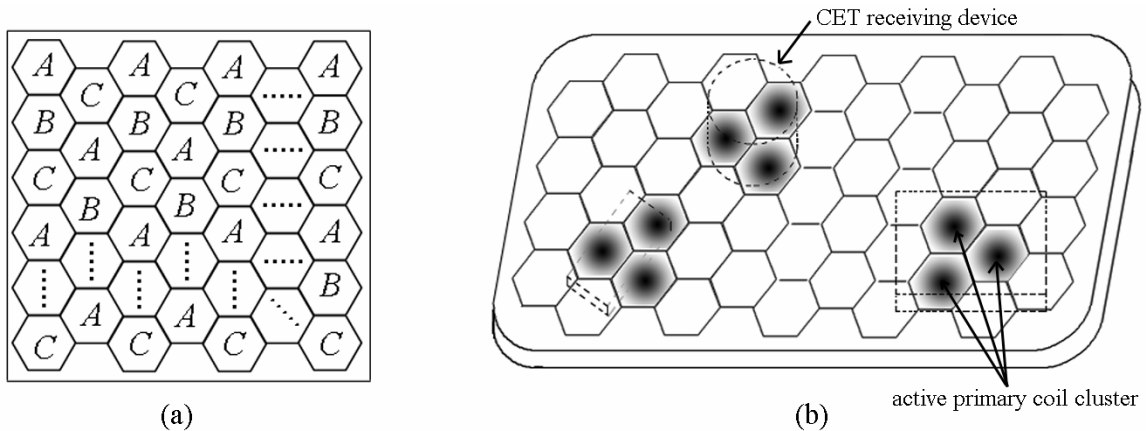
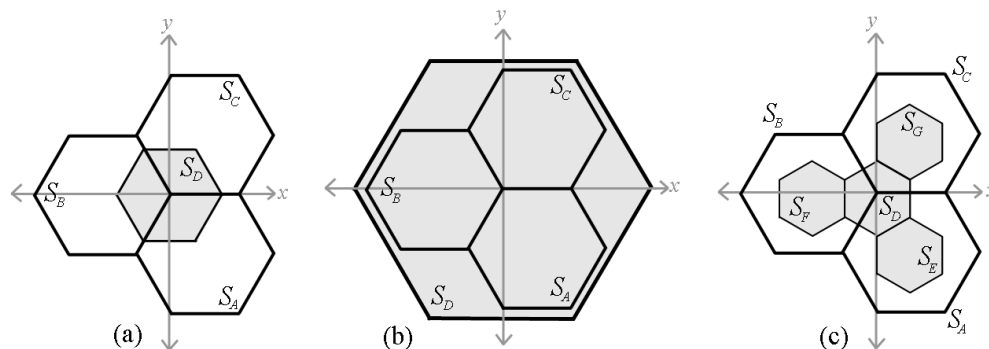


Fig. 3: (a) A matrix of hexagon spiral windings, showing the individual current phase angles, and (b) the CET desktop application showing three clusters of activated primary coils powering the CET “receiving devices” placed thereupon.

Specialized CET receivers

One important requirement of the CET desktop application is that it should be able to transfer power to receiver devices placed on the table, independent of their position and orientation. The need for specialized receivers arises from the fact that the magnetic field distribution, the electromagnetic coupling and finally the power transfer capability and efficiency of a single receiver coil vary with its relative position to the primary coils. The absolute magnetic field distribution as well as the perpendicular component of the field above a primary hexagonal coil are triangular in shape, with a maximum value above the center of the winding, and a near zero value at its edges. This large variation in the field causes large variations in the electromagnetic coupling between parallel-and-laterally displaced coils, with near zero coupling between coils shifted by a one radius distance. Figure 4(a) shows such a situation, where minimal coupling between the primary coils S_A , S_B and S_C and the secondary coil S_D , will cause a minuscule or zero transfer of power. Furthermore, for the magnetic field shaping method [1] to work properly, all three excited primary coils inside an activated primary coil cluster must be excited with the same current amplitude, but with 120° shift in phase. This localizes the magnetic field to the area of the coil cluster and reduces the stray magnetic fields by destructive interference caused by the individual out-of-phase magnetic fields. Unfortunately, a situation may arise when using a secondary coil with a radius larger than that of the primary coils, where the electromagnetic coupling between the individual primary coils and the secondary coil is approximately equal. In such a case the individual induced secondary voltage amplitudes are roughly equal, but 120° out-of-phase, which results in a zero net voltage, and no transfer of energy. Figure 4(b) shows such a scenario where a large receiver coil S_D is located so that the individual primary-to-secondary couplings are approximately equal. To overcome the position sensitive power transfer inherent to the CET desktop application, specialized receiver configurations are used. By using multiple small receiver coils, they can individually draw power from the closest primary coil, which can then be regulated or rectified and combined to power the load. Fig 4(c) shows such a situation where the receiver coil configuration will still be able to draw power from the primary coils, despite bad coupling for the middle coil.



(a) With no (or extremely low) individual coupling between the primary coils (S_A , S_B , S_C) and the secondary coil (S_D), no voltage is induced in the secondary coil, and thus no power is transferred.

(b) With equal individual coupling between the primary coils (S_A , S_B , S_C) and the secondary coil (S_D), the out-of-phase currents will induce out-of-phase voltages at the secondary coil. With a zero net voltage at the secondary, no power is transferred.

(c) Multiple smaller secondary coils have different individual primary-to-secondary couplings allowing individual power transfer from the closest primary coil.

Fig. 4: (a, b) A receiver coil configuration where minimal or no power will be transferred to the secondary coils due to the inherent limitations of the system. (c) A receiver coil configuration which will be able to draw power from the primary coils.

The design of position independent receiver configurations is an iterative process where the characteristics, sizes, positions and amount of individual receiver coils should be altered until the power transfer requirements for the receiver are met. Since every CET receiver device could have different size constraints and power needs, the receiving coil topology will most possibly be different for each application. Because of this, the focus of this paper is not to design an optimal receiver for one particular application, but rather present methods to evaluate and compare different coil assemblies, which in turn can be used to find optimal receivers for a variety of applications.

Evaluating the specialized CET receivers

In order to assess the different receiver coil topologies and determine their ability to stabilize the position sensitive power transfer, they are put through an evaluation process. The evaluation process starts by determining an evaluation area wherein the receiver coil cluster is simulated. The primary coil cluster and the receiving coils are separated vertically by approximately 5 mm, which corresponds to the practical setup, where the primary coil matrix is embedded roughly 2 mm under the table surface and the secondary coils are located approximately 3 mm above the desk. From the center of the primary coil cluster an evaluation area ranging from -3 to +3 times the primary coil radius in both the x - and y -directions, is used (Fig. 5(a)).

Secondly, the lumped parameters for the primary and secondary coils are estimated using the lumped inductor model presented in [1]. They are estimated by using Maxwell 3D version 11 (Ansoft Corporation) and simulating the coils in a 3D environment. The series inductances are calculated using the magneto-static solver and the AC-resistances are determined using the eddy current solver. Alternatively, existing analytical or numerical methods can also be used to acquire the values.

Thirdly, the mutual inductances and the electromagnetic coupling between all the coils in the primary and secondary coil clusters are estimated by simulating them in Maxwell 3D and using a magneto-static solver. The evaluation area is divided into a matrix of discrete positions, each separated from the other by 1 mm in the x' - and y' -directions, respectively (Fig 5(a)). The electromagnetic coupling between all the coils is calculated at every position in the evaluation area and stored in a lookup table for later use.

Finally, the maximum apparent power transfer efficiency between the primary and secondary coil cluster is calculated for every discrete position in the evaluation area. This is done by using a simplified version of the CET power transfer model [1]. Figure 5(b) shows a schematic representation of the simplified power transfer model. The three primary circuits are on the left, with V_A the voltage source, R_A and L_A the series resistance and the self inductance of the coil, and i_A the current of the first primary circuit. M refers to the mutual inductances between the different coils, and are indexed with the appropriate subscripts. There are three primary circuits A , B , and C , and the amount of secondary circuits is given as Q , ranging from $C+1$ to $C+Q$. They are located on the right in Fig 5(b).

The apparent power transfer efficiency is calculated by first writing the circuit equations. The circuit equations for the primary circuits are given as:

$$V_p = R_p i_p + \sum_{k=A}^{C+Q} \left[M_{pk} \frac{d}{dt} i_p \right], \text{ where } (A \leq p \leq C), \quad (1)$$

and the circuit equations for the secondary circuits as:

$$0 = Z_q i_q + R_q i_q + \sum_{k=A}^{C+Q} \left[M_{qk} \frac{d}{dt} i_q \right], \text{ where } (C+1 \leq q \leq C+Q). \quad (2)$$

This results in a set of $3+Q$ differential equations, which are solved by converting them into matrix representations and then manipulating those matrices into a state-space representation. Using Simulink (The MathWorks, Inc.) the circuit equations and currents are solved for a range of different load resistances and input voltages [1]. On the basis of sinusoidal input voltages, using the steady-state, RMS current values from the Simulink model output, the maximum apparent power transfer efficiency (using matched loads) is given as:

$$\eta_s = \frac{\sum_{n=C+1}^Q I_n^2 Z_n}{(V_A I_A + V_B I_B + V_C I_C)} \times 100\%, \quad (3)$$

where the RMS values for the voltages and currents are used. Using (3), the maximum apparent power transfer efficiency, η_s , is calculated at every discrete position in the evaluation area and stored in the efficiency-position graph.

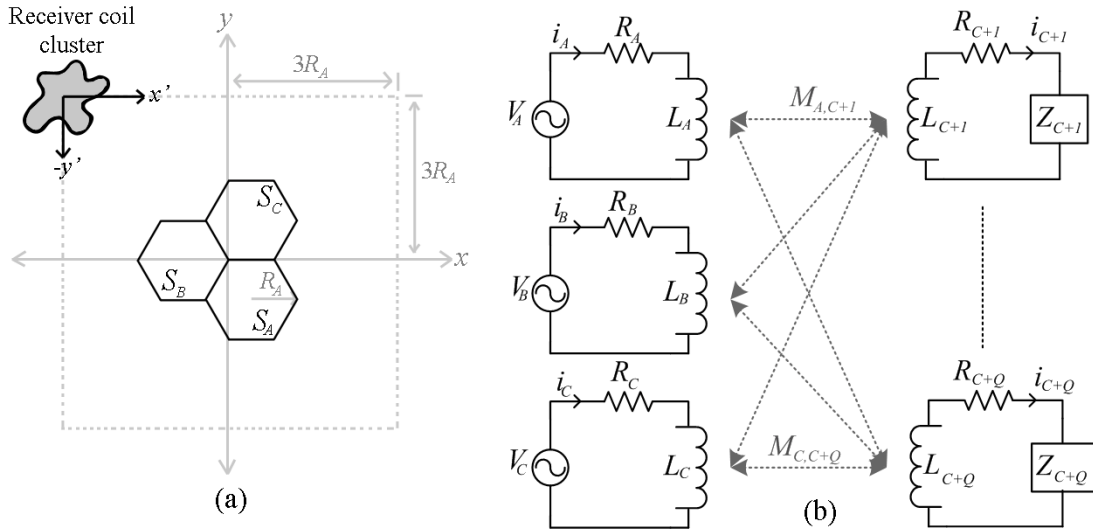


Fig. 5: (a) The evaluation area around a primary coil cluster. (b) A simplified representation of the multi-port transfer model. The three primary circuits and coils are on the left, secondary circuits and coils are on the right.

The result of the evaluation process is a three-dimensional efficiency-position graph which shows the power transfer efficiency as a function of the relative position of the primary and secondary coil clusters. High peaks or “hills” denote areas of high power transfer efficiency and low values or “valleys” indicate areas of reduced power transfer efficiency. Receiver coil configurations that show graphs with multiple hills and valleys tend to be more position sensitive. The aim is to narrow the gaps between the hills and valleys and make the graph as “flat” as possible, as to make the receiver more position insensitive and produce a stable transfer of power independent of secondary coils’ positions.

Simulation of specialized CET receivers

To demonstrate the simulation and evaluation process, two different receiver coil configurations are simulated. In these power transfer calculations, the maximum efficiency is predicted by simulating a wide range of load resistance values. The load resistance which gives the maximum transfer efficiency (matched load) is then used. This is done at every position in the evaluation area.

Receiver Type 1: Single hexagon spiral winding receiver simulation

In the first set of simulations, the efficiency-position graph of a single hexagon spiral winding receiver coil is estimated. The secondary hexagon spiral winding shown in Fig. 7(b) has the same dimensions as the hexagonal windings used in the primary coil structure (Fig. 7(a)), and are given in Table I. An evaluation area of -120 mm to 120 mm in both the x' - and y' -directions are used. The receiver coil is evaluated at a distance of 5 mm above the primary coil cluster (Fig. 7(c)).

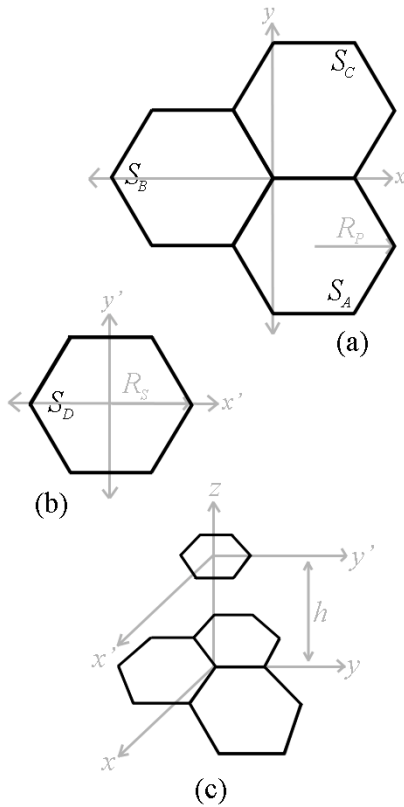


Fig. 7: (a) The primary coil cluster, (b) the receiver coil and (c) the positioning of the primary and secondary coil cluster during the evaluation process.

Table I: Physical dimensions and electrical properties of a hexagon spiral winding.

Parameters	Value
Hexagon spiral winding inductance	14.8 μH
Hexagon spiral winding resistance	1.95 Ω
R_P and R_S (Outer radius)	40 mm
Track width	1 mm
Inter track spacing	0.5 mm
Turns	23
Copper thickness	30 μm
Simulation frequency	150 kHz
h (z-distance between primary and secondary coils)	5 mm

Figures 8(a) and (b) show the results of the simulation. From Fig. 8(a) three distinctive high-efficiency locations can be seen. As expected, they correspond to the centers of the primary coils. Due to the lack of sufficient coupling and the three-phase cancellation effect, a large “dead spot” can be seen in the area between the three coils. The simulation shows a maximum power transfer of approximately 13 %. From these results it can be concluded that a single receiver coil of this size and dimensions will not be sufficient for use in the CET application desktop, because it is too sensitive to receiver coil placements.

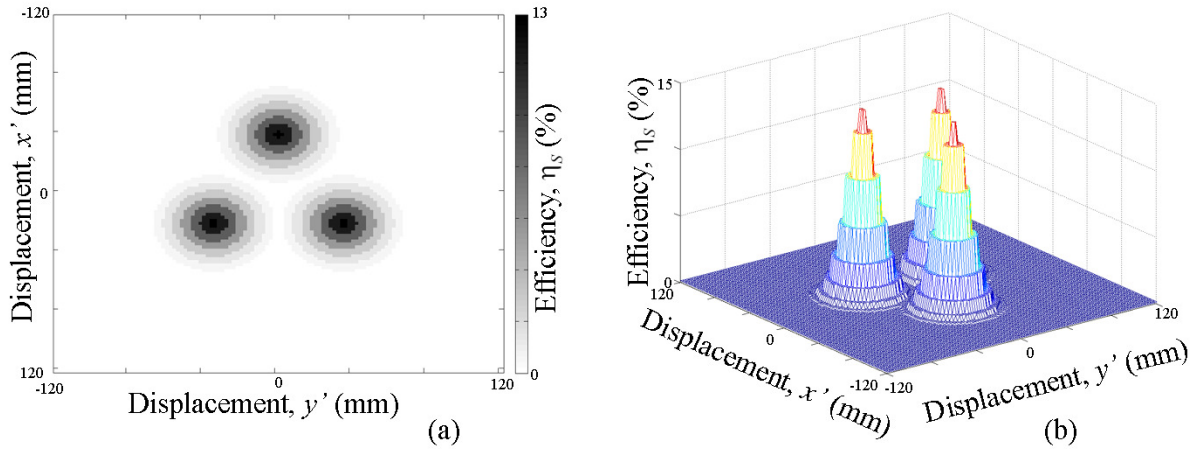


Fig. 8: (a) Two-dimensional (top view) – and (b) three-dimensional efficiency-position graph for the first set of simulations.

Receiver Type 2: Seven-hexagon spiral winding receiver simulation

In the second set of simulations, the efficiency-position graph of a seven-hexagon spiral winding receiver (Fig. 9 (b)) is simulated. The primary coil cluster (Fig. 9 (a)) and the evaluation area remains the same as in the previous simulations. The receiver coils are evaluated at a distance of 5 mm above the primary coil cluster, as shown in Fig. 9(c).

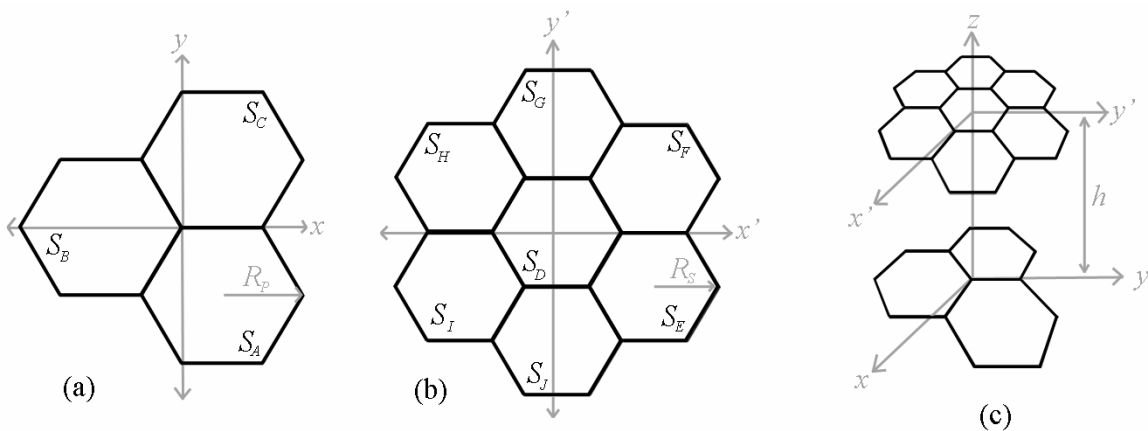


Fig. 9: (a) The primary coil cluster, (b) the seven-hexagon spiral winding receiver coil cluster and (c) the positioning of the primary and secondary coil cluster during the evaluation process.

The dimensions and electrical properties of the primary hexagon windings S_A , S_B , and S_C are given in Table I, and the properties of the seven secondary hexagon spiral windings in Table II.

Figures 10(a) and (b) show the results of the second set of simulations. From Fig. 10(a) one high-efficiency peak and 15 smaller peaks can be seen. The maximum power transfer efficiency of approximately 11 % in the center of the graph is noted, and the results show no “dead spots”. From these results it can be concluded that the seven-hexagon spiral winding receiver is better suited for the CET desktop application than the single receiver coil.

Table II: Physical dimensions and electrical properties of a single secondary hexagon spiral winding.

Parameters	Value
Hexagon spiral winding inductance	75 μ H
Hexagon spiral winding resistance	12 Ω
R_s (Outer radius)	20 mm
Track width	0.2 mm
Inter track spacing	0.1 mm
Turns	66
Copper thickness	30 μ m
Simulation frequency	150 kHz
h (z-distance between primary and secondary coils)	5 mm

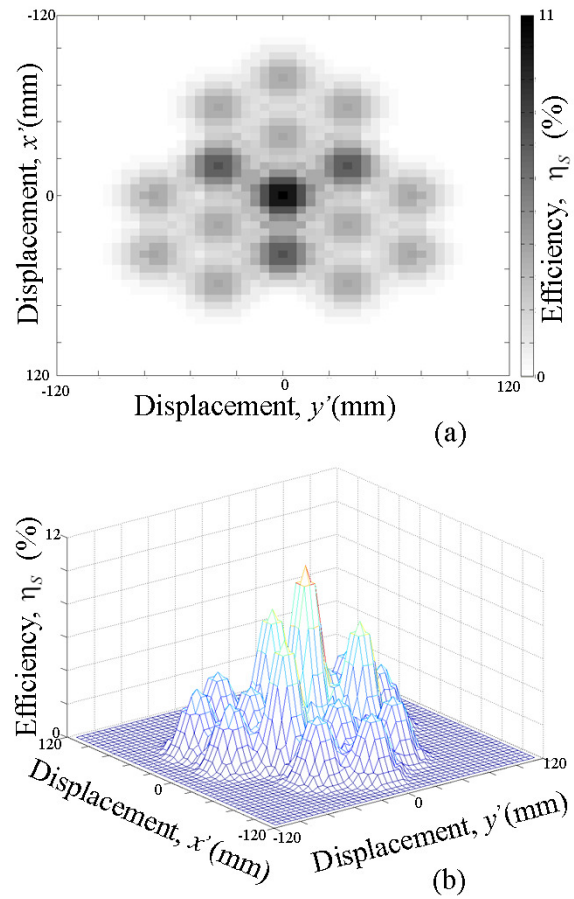


Fig. 10: (a) Two-dimensional (top view) – and (b) three-dimensional efficiency-position map for the second set of simulations.

Conclusions

In this paper, a new CET desktop application is presented. The CET desktop utilizes a matrix of hexagon spiral windings embedded underneath its surface, to transfer power to consumer electronic devices, embedded with “receiving coils”, placed on the table. Power is transferred through inductive coupling between the primary and secondary coils. The CET desktop attempts to improve efficiency and reduce stray magnetic fields, by activating clusters of three primary coils located closest to the individual receivers. Additionally, stray magnetic fields are reduced by employing the magnetic field shaping technology presented in [1]. Unfortunately, due to the design of the CET desktop, the magnetic field distribution from the hexagon spiral windings used in the desk is not uniform. This causes non-uniform electromagnetic coupling and a power transfer efficiency that varies with different receiver placements. Presented in this paper, is a method for designing and evaluating different receiver coil configurations to determine the efficiency of different coil topologies and at the same time attempt to stabilize the power transfer and to make it more position insensitive. The evaluation process can thus be used to find optimal receivers for a variety of different applications. From the two sets of simulations presented in this paper, it is seen that receiver coil topologies with multiple small receiver coils are better suited for transferring energy than a single large coil.

Recommendations

From the two sets of simulations presented in this paper, maximum efficiencies of 13 % and 11 % are predicted, respectively. These values are extremely low and not practical. To boost efficiency however, resonant capacitors in the primary and secondary side of the CET link can be used so that the capacitive reactance compensates for the coils' inductance reactance, reducing the inductors effective impedance and increasing the power transfer efficiency. A practical CET desktop application employing resonant capacitors will thus have a higher efficiency than the values stated in the simulations.

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