Variable Position Wireless Power Transmitter through Multiple Cooperative Flux Generators

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***Abstract*— Wireless power transfer systems have become more commercially viable and applicable in the recent decade. Research interests have been focused on solving the inherent challenges that implementation of this technology engenders, which include elimination of electromagnetic field energy broadcast combined with spatial freedom of power transfer to receiver systems. The solutions to these two challenges require confining EM flux only to receiver systems and having an arbitrary large area for power transfer. This work presents a novel power transmitter system which tackles these two challenges by producing a simplistic moveable electromagnetic energy field over an arbitrarily large area by switching transmission coil configurations. The transmitter system is validated against the wireless power Qi™ standard limits for adequate power transfer efficiency. This new transmitter accomplishes spatial freedom and EM field confinement to charging systems while maintaining simplicity in construction and control.**

Keywords- Inductive power transfer, Wireless Power Consortium, spatial freedom, configurable EM field, Wireless Energy Transfer

I. Introduction

In recent years, wireless power systems (WPS) using coupled electromagnetic fields have become increasingly common in commercial applications. It has been demonstrated that the efficiency of any system that transfers power through inductively coupled coils is inversely proportional to the spatial separation between the center point planes of those coils [1]. However, the non-trivial expectation of spatial freedom of subsystem placement while maintaining efficient energy transfer between the coils of the transmitter (Tx) and receiver (Rx) subsystems, has become a major requirement for widespread adoption of the technology. Achieving this challenge has been a major topic of WPS research.

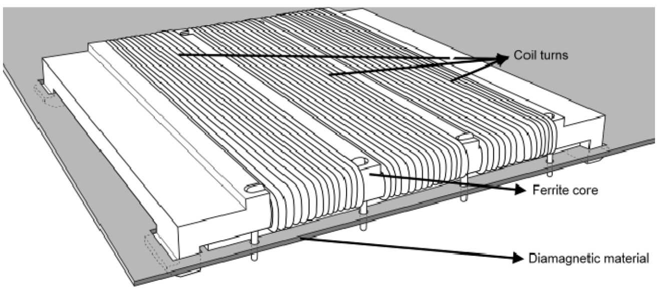

Figure 1. Conception drawing of three-coil PCA, showing the windings, the common core, and the diamagnetic substrate

Approaches to this challenge by other researchers include allowing the perception of free positioning through the selective combination of numerous overlapping small coils [2]. This approach not only requires a significant number of coils, but a proportionately large and complex control electronics scheme. Another approach delivers power to an arbitrarily large area with a single coil, but can require inductors of very high Q [3]. Furthermore, in this type of system it can be difficult to control the transfer of energy into unintended devices that are in the Tx-generated field range [1]. A single large coil will generate a field that is intercepted by the intended receiver subsystem(s), but there is no mechanism to prevent an unintended tuned object from converting the magnetic field into an unexpected current or heat due to the electromagnetic field 'broadcast' from the transmitter.

This paper describes a novel method of achieving spatial freedom with simple coils configured to work alternately in pairs in order to provide highly coupled and efficient power transfer on the whole transmitter pad. Furthermore, this transmitter design implements a reduction in EM field broadcast by alternately turning off coils which are not being used in power transfer, without sacrificing the minimum efficiency needed for adequate transfer as defined by the international wireless power transfer standards. It shows that multiple coils used in conjunction can effectively create a movable flux-generating region with high coupling coefficient to a receiving coil with relatively simple control electronics.

II. Variable Position Wireless Power Transmission through Cooperative Flux Generators

The method proposed in this research by which arbitrary positional freedom can be achieved makes use of multiple copper windings wound around a common ferrite core ($\mu >> 1$) which is substantially longer and wider than it is thick. Each of the windings is of similar length, width, and number of turns, and is constructed of wire of similar material and gauge. Located beneath the coil is a layer of diamagnetic material. This construction is known as the primary coil array (PCA), which along with basic control electronics constitutes the transmitter subsystem (Tx).

To generate the movable flux field using the PCA, the PCA coils are operated in pairs at any particular time, determined by the relative position and coupling between the Tx subsystem and the receiver subsystem (Rx) to which power is being transferred. The coil pair switching is controlled by a simple electronics control system. The operating coil pair are connected in anti-series, such that the current through each of them will be identical but the flux generated in the shared core will be in substantially opposing directions. The diamagnetic layer on the underside of the core reduces the leakage inductance of the PCA when coupled to a receiver coil subsystem. This in turn reduces the current needed in the PCA to achieve a given output current, resulting in smaller losses due to parasitic resistance in the PCA. The possible coil pair configurations for this system are such that the two coils are either adjacent to each other on the core ("adjacent pair", AP), or the outer two coils in PCA are used ("internal unused pair", IUP) as illustrated in Fig. 2. When a coil pair is selected, it can be considered as an inductor with inductance L_{p}.

The system is used as a WPS by introducing the receiver subsystem above the Tx subsystem. The Rx coil is constructed of several windings wound in a spiral pattern, all in the same plane. The plane of the winding is parallel to the long axis of the core in the coil array, and is thus orthogonal to the winding axis of the coils in the Tx subsystem. This second coil is also considered as an in inductor, with inductance L_s.

An alternating current flowing through inductor L_p will generate a magnetic flux field linking the second coil L_s, hence forming a transformer with coupling coefficient k, such that $k = M / \sqrt{L_p \bullet L_s}$, where M represents the mutual inductance between inductors L_p and L_s. The value of k at a given location is a figure of merit for this work in a manner that is analogous to a WPS as described by the Wireless Power Consortium standards for coupling between transmitter and receiver subsystems [4]. The standard stipulates that wireless power transfer will be possible with any value of $k > 0.25$. The area of sufficient coupling (ASC) can thus be defined as the maximum area in which the center of Rx coil is offset from the center of an AP or IUP, and the condition $k > 0.25$ is still met.

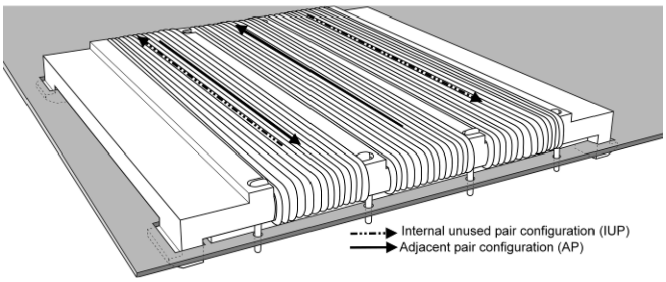

Figure 2. The two configurations of coil pairs (AP and IUP) with arrows indicating simultaneous current directions per coil

The proposed 3-coil PCA array can be extended to any arbitrarily length by adding additional coils and extending the length of the core. If the ASC of a proximate AP and IUP overlap for a given L_s on a PCA, then it can be said that spatial freedom is achieved for the PCA and L_s.

The plot in Fig. 3 shows a finite element analysis of the PCA (in IUP configuration) linked to an Rx coil. It is clearly visible that the flux generated by the two energized coils in the PCA is linked to the secondary coil.

III. EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup consisted of a 53mm x 53mm x 2.5mm tile of NiZn ferrite (Fair-rite™ Material 44) around which was wound 20 turns (2 courses of 10 turns each) of litz wire made of 5 bundles of 26 strands of 0.08mm diameter wire. The coils were wound such that each coil was 12mm wide.

The coils were spaced with approximately 3.33mm between the outer coils and the outer edges of the ferrite tile. There was an approximately 6.67mm gap between adjacent coils on the tile. This spacing allows for a consistent spacing between coils if multiple tiles are placed proximately. Beneath the coils is a copper sheet (diamagnetic layer) of dimensions 53mm x 53mm x 0.1mm as seen in Fig. 4.

The specific Rx coil rectangular configuration used is constructed to the specifications of the "Power Receiver example 1" of the Wireless Power Consortium Qi™ standard [4]. This Rx subsystem was chosen to illustrate potential compatibility between the PCA and the Qi™ transmitter. The PCA was mounted to a computer controlled positioning system, capable of two-dimensional movement (XY table), 20mm in either direction from a reference origin (centre of PCA) in 1mm increments. The Rx coil was mounted 5mm above the PCA with the same reference centre. The two subsystems were then connected to an LCR meter and the inductances M, L_p, and L_s were measured at each position, from which k was calculated with a 100kHz $1V_{RMS}$ input test signal. Fig. 5 illustrates the experimental setup.

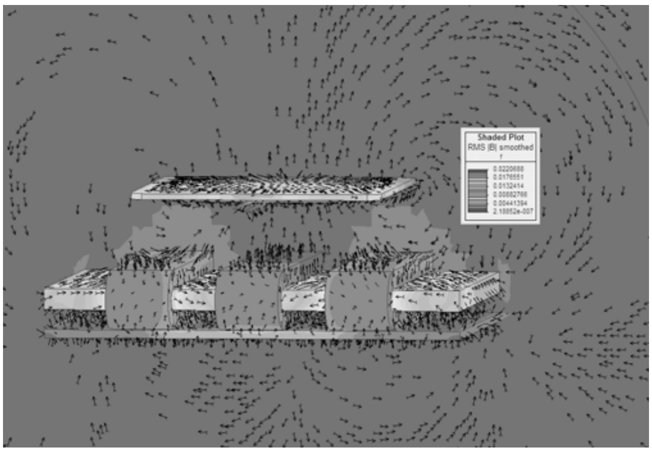

Figure 3. Finite element analysis of the construction, showing B field intensity and flux linkage from the PCA to L_s

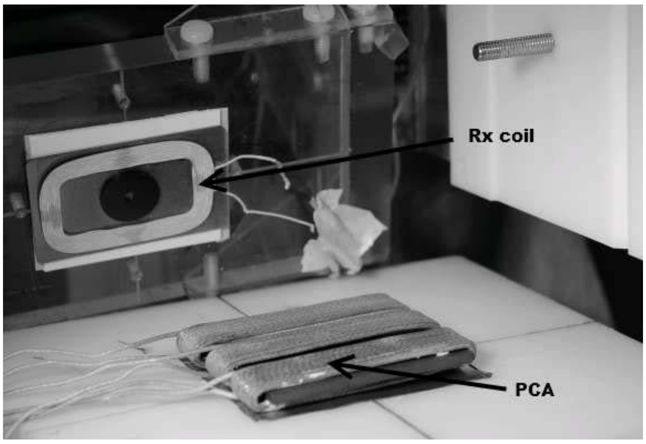

Figure 4. Coil types used in the experiment. Rx coil and the PCA

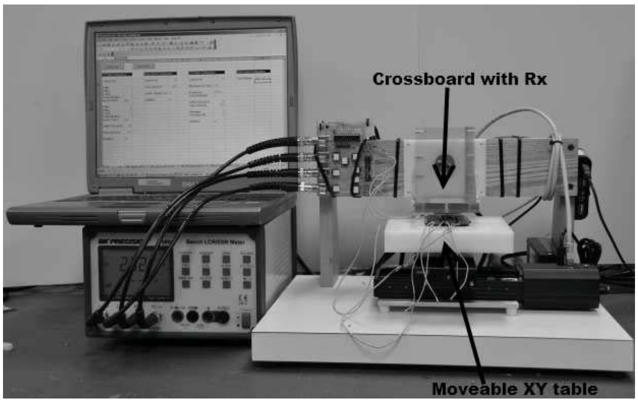

Figure 5. The experimental setup. Visible are the XY positioning table, the Meter, and the computer the control. Rx coil is mounted in a fixed position to the cross board. The PCA is mounted to the movable table.

IV. Results And Discussion

The AP and IUP configurations were both evaluated with the above test procedure. Surface maps were created that show the calculated value of k_{xy} at each incremental step in either (x,y) direction of the reference origin as shown in Fig. 6a and 6b.

It can be seen in the AP configuration that the ASC encompasses a region from approximately 15mm left of the center of the PCA to approximately 3mm to the right of the center point, and from points approximately 20mm above and below the center point. The AP that was mapped in Fig. 6a is the leftmost pair, and it can be assumed that the rightmost pair will have an ASC that is the mirror image of the leftmost pair. Similarly, the ASC for the IUP configuration encompasses a region from approximately 7mm left of the center of the PCA to approximately 7mm to the right of the center point, and from points approximately 20mm above and below the center point.

If the *k*-value plot for the left AP, the IUP, and the right AP are superimposed as in Fig. 6c, the combined area would encompass a region from approximately 15mm in either x-direction of the reference center, and 20mm in either y-direction of the reference center, which satisfy the ASC condition necessary for adequate power transfer, as stated by the Qi™ standard. The coil inter-switching to achieve this region is controlled by a simple control system that monitors *k* and changes coil pairs accordingly. By extension, a PCA that is constructed of more than three coils could be constructed to have an effective ASC of arbitrarily longer length, and from 20mm above and 20mm below the centerline.

V. Conclusion

The study showed the novel construction is a good candidate for a wireless power system with arbitrarily large spatial freedom that satisfies the efficiency requirements as specified by the Qi™ standard. This construction allows for benefits of efficiency, protection from transfer of energy into unwanted subsystems, and standardization for commercial use due to a closely aligned WPS. It also allows an experience of spatial freedom that enhances usability, and simplifies implementation due to the coil constructs and the relatively simple control circuitry. In addition, it covers more area per given coil than other proposed coil arrays in the present Qi™

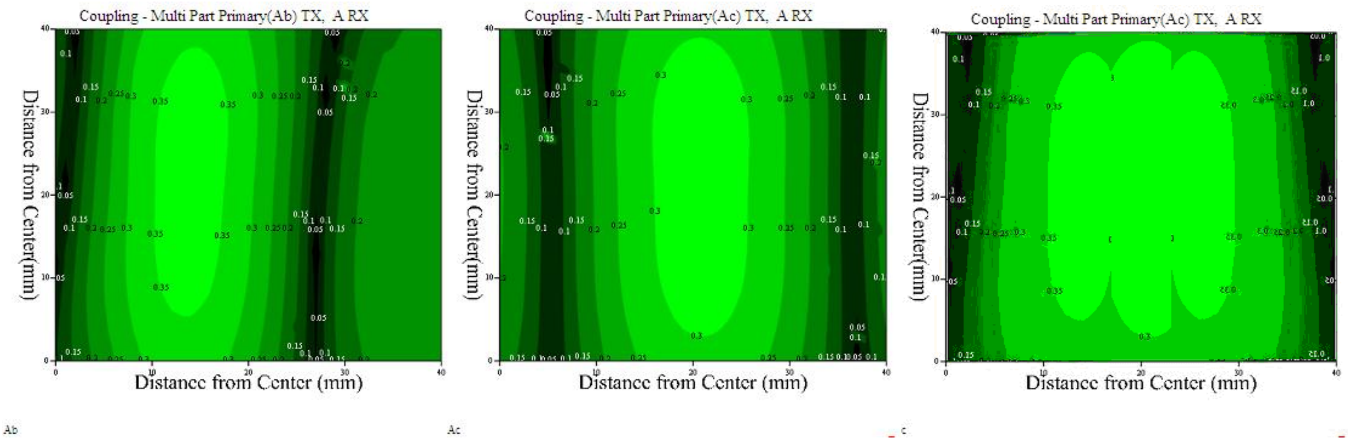

Figure 6. Coupling Maps for PCA coil pair configurations: *a).* AP, *b)* IUP *c)*.Superposition of AP, IUP, AP.

standard, while simplifying the power electronics needed to drive the array and reducing the cost of its implementation.

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