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Design and study of multi-dimensional wireless power transfer transmission systems and architectures

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ABSTRACT

This paper reports on the design of multidimensional wireless power distribution using cellular concept, Helmholtz coils and cubical node design with power transmission capability over a distance of 6 m. To provide strong and uniform power delivery along the power transfer link axis, pairs of Helmholtz coils which are capable of creating uniform magnetic fields are used. To distribute wireless power in multiple dimensions the transmitter containing six secondary coils and one primary coil were used. The secondary coils orient magnetic files in six directions and the primary coil provides power transfer in the vertical direction. A cellular concept which permits the planning of power transfer over wide area is proposed. Furthermore, we have used a class E power source to power the transmitter. Class E power amplifiers provide stable resonant outputs to which the transmitter responds in sympathy. They also provide high voltage outputs and low currents making them safe for high voltage operations. The proposed cellular architecture with the multidimensional transmitter and receivers are demonstrated to be an excellent choice for inductive wireless power distribution over long distances. The multidimensional transmitter behaves like an inductive power coupler. With only one multidimensional transmitter and receivers, a range of about 6 m has been achieved end to end. The cellular architecture allows the power transfer network to be planned. Further range extension can be achieved by using a relay coil placed 9 cm above the primary coil.

Introduction

Transmission lines have historically been used for distribution of electric power over long distances and wide area. However unlike normal electric power transmission, the application of transmission lines are not suited for inductive wireless power distribution since doing so negates the very essence of wireless power transfer. Hence new paradigms are required for wireless power transmission and distribution over wide areas and long distances. In this paper a cellular concept similar to cell planning in mobile communication is proposed. Cellular power sources can result in wide area wireless power distribution provided issues dealing with crosstalk and rapid decay of inductive power are tackled. A great deal of effort is required to reduce crosstalk between neighbouring coils in inductive systems. At the moment, this problem remains unsolved and all resonant systems are susceptible to crosstalk of some sorts. Hence establishing the optimum locations of resonant coils to enhance power transfer remains an area of research interest in wireless power transfer and inductive communication systems. In most cases trial and error methods are used to ascertain the best locations for the transceivers. Poor placing of the coils leads to not only crosstalk but also frequency splitting so that maximum power is not transferred at the required resonant frequency.

Historically, Nikola Tesla in 1927 conjectured with experiments the possibility of broadcasting wireless energy round the globe [1]. Nikola demonstrated that both radio waves and inductive methods can be used. The telecommunications field is also awash with different forms of wireless broadcasting of electromagnetic waves including long waves, short waves, ultra high frequency (UHF) radio, television (TV), mobile communications (GSM, GPRS, UMTS, PCS and 4G) to wireless local area networks (WLAN) to mention a few. These forms of RF broadcasting are all used for transferring of data in electromagnetic forms but rare for transport of electrical power for lighting houses and equipments. In the real sense they may be used for that purpose but the commercial intentions have never been for that and hence the modern re-discovery of wireless energy transfer may be termed a new paradigm for harvesting, generation, transmission and distribution of electrical energy. While a great deal of effort has been dedicated to demonstrating wireless power transfer over tens of centimetres, there remains the need for demonstrating distribution of wireless power transfer

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(WPT) in many directions, to large distances and over only desirable locations. Some of the concepts required for achieving these expanded scope of WPT have been used in one form or the other in electric motors, generators and synchronous machines worldwide, in turbines and for generation of the traditional 50 Hz (60 Hz) electric power to homes and industries. Interestingly as more and more new applications of inductive wireless power transfer emerges, it is clear that some applications require focused and directed magnetic fields into desired directions, with preferred gradients and of preferred beamwidth. Several essential requirements need to be met. Four of such requirements for resonant wide area WPT systems are the following. Firstly, both the transmitter and receiver must resonate at the same operating frequency. Secondly, power should be transferred over reasonably long distances. Thirdly, the magnetic fields need to be focused. Fourthly, the magnetic fields should be constrained to only desirable directions and for safety purposes away from other areas such as field-free zones.

Different applications require different field characteristics. For robotic propulsion and navigation [2–4], uniform magnetic fields are required. In autonomous navigation of micro robots [22] uniform fields with desirable gradients not only ensures directivity of the robot but also propulsion with the required optimum magnetic force. To achieve this in micro robot navigation [3], two Helmholtz coils [2,4] are used to create a uniform magnetic field between them. The uniform field orients a micro robot in a desired direction. Then two Maxwell coils carrying currents in opposing directions are used to create a propulsion magnetic force for the micro robot [2–4]. Magnetic field coding could greatly enhance the design of such systems to ensure decoupling of the direction of propulsion from the orientation [3,4] and control [22] of micro robots and reduce crosstalk.

Furthermore there is possibility for green energy using inductive energy transfer in homes. This requires the magnetic fields to be focused, be multi-dimensional and for safety reasons also provide field-free zones in homes. Furthermore, shaping of the magnetic fields by the inductive transmitters and how to plan networks of inductive receivers could enhance the use of inductive energy transfer systems in homes and desktop wireless chargers [21]. In applications such as inductive wireless powering of homes and desktop chargers, safety and health concerns make it undesirable to have induced magnetic fields everywhere. It is therefore essential to direct the magnetic field away from areas which should be free of magnetic fields. Unfortunately to date, there are no reported techniques for doing this.

It has been observed that magnetic fields are not affected by multipath impairment as are electromagnetic waves. Magnetic fields are also relatively immune to reflection, diffraction and the effects of their environments provided there are no magnetic materials there. These advantages make magnetic fields suited to sensing in environments where the effects of the environment could be severe with electromagnetic radiation such as in anti-collision systems in transportation and vehicular networks. Although the application of resonance coupling in vehicular anti-collision radar systems is yet to be reported, it has the potential to outperform anti-collision systems based on linear frequency modulated continuous wave (FMCW) technologies [9]. FMCW anti-collision can determine both the velocity and the proximity of a nearby vehicle using Doppler frequency shifts and large system bandwidth. Resonance methods need not use large bandwidth systems and velocities can be determined based on the coupling coefficients in the system. Recently anti-collision systems using RFIDs have been studied [10–12] but suffer from co-channel interference and hence inability to identify tags. Collisions from multiple tags responding to beacon transmissions limit performance. To reduce this problem elaborate medium access techniques were developed by several authors [10–12]. However, in a busy highway, multiple collisions will limit the determination of accurate positions and speeds of interfering vehicles [6–8].

Wireless power transmissions with two coils over distances of more than 1 m are rare. Normally to increase the transmission range three to four resonant coils are used as in [17–20]. This paper introduces a new design based on a cubical structure which permits simultaneous power distribution in many directions and over 'very large' distances of up to 6 m. Only two coils are involved in power transmission along a given axis.

The rest of the paper follows the following format. In section 'Wide area energy transfer architecture' we propose a new design framework for distributing inductive wireless power into many directions with enhanced range. A cellular architectural framework is presented for multiple input and multiple output configurations. Experiments are conducted and measurements of the induced voltages are given over a spherical surface centred on the transmitter. In section 'Hardware implementation', implementation of multi-dimensional flux design and distribution system networks is given. Section 'Cellular wide area wireless power distribution' develops the proposed cellular wireless power distribution network. In this section we also design and implement a class E input power source. Section 'Experiments and results' describes a series of validation experiments based on our hardware design. The application section, describes areas where the multi-dimensional WPT system may be used. Conclusions are drawn in section 'Conclusions'.

Wide area energy transfer architecture

Recently we proposed flux concentrators and separators as building template for wide area wireless power transfer systems with reduced crosstalk [5]. While the techniques in [5] have applications in wide area communication systems, body area networking and Internet of things architecture, they are however not able to create flux free zones and do not demonstrate how effective multidimensional focused magnetic fields could be created. A multidimensional wireless power system broadcasts wireless power. It is defined as arrays of inductive power transmitters separated from each other by receivers and arranged in inductive power cells to power large geographical area. The basic building block is the binary multiple-input-single-output (MISO) cell shown in [5] (Fig. 1). In the binary MISO, two transmitters (TX) are used to create the required magnetic field for a receiver (Fig. 1(a). The objective of the binary MISO system is to increase the inductive power to a receiver with reduced crosstalk. By doubling the distance to (2r) between the transmitters in (Fig. 1(a)), the crosstalk between them is reduced considerably. When used for data communication, it also leads to increased data capacity as demonstrated in [5].

A binary SIMO is shown in Fig. 1(b) in which one transmitter feeds two receivers placed on either side at equal distances. In this case if the receivers are identical they intercept equal amounts of inductive energy. Also the crosstalk between them is reduced considerably because the separation between them is doubled [5].

In the next sections we propose how to use this binary architectural framework of Fig. 1 for creating (a) a wide area inductive wireless energy transfer system (b) for ensuring a region free of magnetic field and (c) for multi-dimensional focusing of magnetic fields. Matlab simulations and hardware evaluation of the proposed systems are provided.

Fig. 1. Binary MISO framework.