Safe Wireless Power Transfer to Moving Vehicles

Investigators
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Abstract

This project explores the feasibility of safe wireless power transfer directly to vehicles cruising at highway speed. We aim to use magnetically coupled resonating coils located in the roadbed and in the vehicles as the power transfer mechanism. In particular, we theoretically showed the difference of the traditional inductive power transfer system and the recently developed resonant inductive power transfer system. We have used large-scale electromagnetic simulations to examine the influence of the body of a vehicle, modeled as a metallic ground plane, on the efficiency of the resonant power transfer scheme and established a preliminary experiment set up of the wireless power transfer system.

Introduction

Electric vehicles offer superior energy efficiency while offering an enormous potential for reducing CO_2 emissions if the electricity is supplied from a renewable or nuclear source. However, they are presently neither range- nor cost-competitive compared to conventional vehicles, due to limited options for recharging, and expensive energy storage (batteries). This project aims at extending the wireless power transfer to the charging of moving electric vehicles. The success of this program may prove to be a very significant step forward towards the possibility of unlimited range electric mobility. By extending the range of electric vehicles, this project will contribute to overcoming a critical limitation of existing electrical vehicles, by offering range at competitive costs.

Background

There has been much previous work aiming to achieve efficient power transfer to both stationary and moving vehicles, some dating back over twenty years[1,2,3,4,5,6,7,8,9]. The majority of these studies used the inductive power transfer schemes. However, it is well documented that there are substantial limitations to an inductive power transfer scheme. The transfer distances are typically below 20*cm*. This has become a substantial issue. For safety reasons, and in order to ensure that the road can still be used for other kinds of vehicles, the source needs to be buried below the pavement. Thus the transfer distance in the inductive power transfer scheme is in fact not sufficient. The lateral tolerance of these schemes is also quite stringent, typically on the order of 10*cm*. Such a stringent lateral tolerance may become a limiting factor for power transfer to a moving vehicle.

In contrast to the more conventional inductive power transfer scheme, our approach here is closely associated with a resonant power transfer scheme[10,11,12,13,14,15]. Similar to inductive power transfer scheme, resonant power transfer occurs through magnetic field coupling. However, in resonant power transfer scheme, both the source and the receiver sides consist of resonant circuits. Efficient power transfer occurs when the two circuits have the same resonant frequency, and when the coupling constant of the two resonances, (which is related to the mutual inductance between the inductors), dominates over the intrinsic loss rates of the resonators.

Using this scheme, a recent experiment[10], which was conducted at MIT, has demonstrated highly efficient power transfer over a distance of approximately $1m$. There are also indications that the resonant power transfer scheme can be far more robust in lateral tolerance compared with the inductive power transfer scheme. Based on this approach, a commercial product of stationary charging pads is already available, with power levels at the kW scale[16]. There has not been, however, a study or demonstration of the feasibility of resonant power transfer scheme to a moving vehicle.

Results

With coupled mode theory based modeling, we present a detail analysis of the traditional inductive power transfer system (illustrated in Fig. 1a, which uses a resonator on the receiver side) and the resonant inductive power transfer system (illustrated in Fig 1d, which uses resonators in both the source and receiver side). Our analysis indicates that the tight tolerance in the inductive power transfer scheme is intrinsic to the scheme, and thus the resonant power transfer scheme is fundamentally more superior.

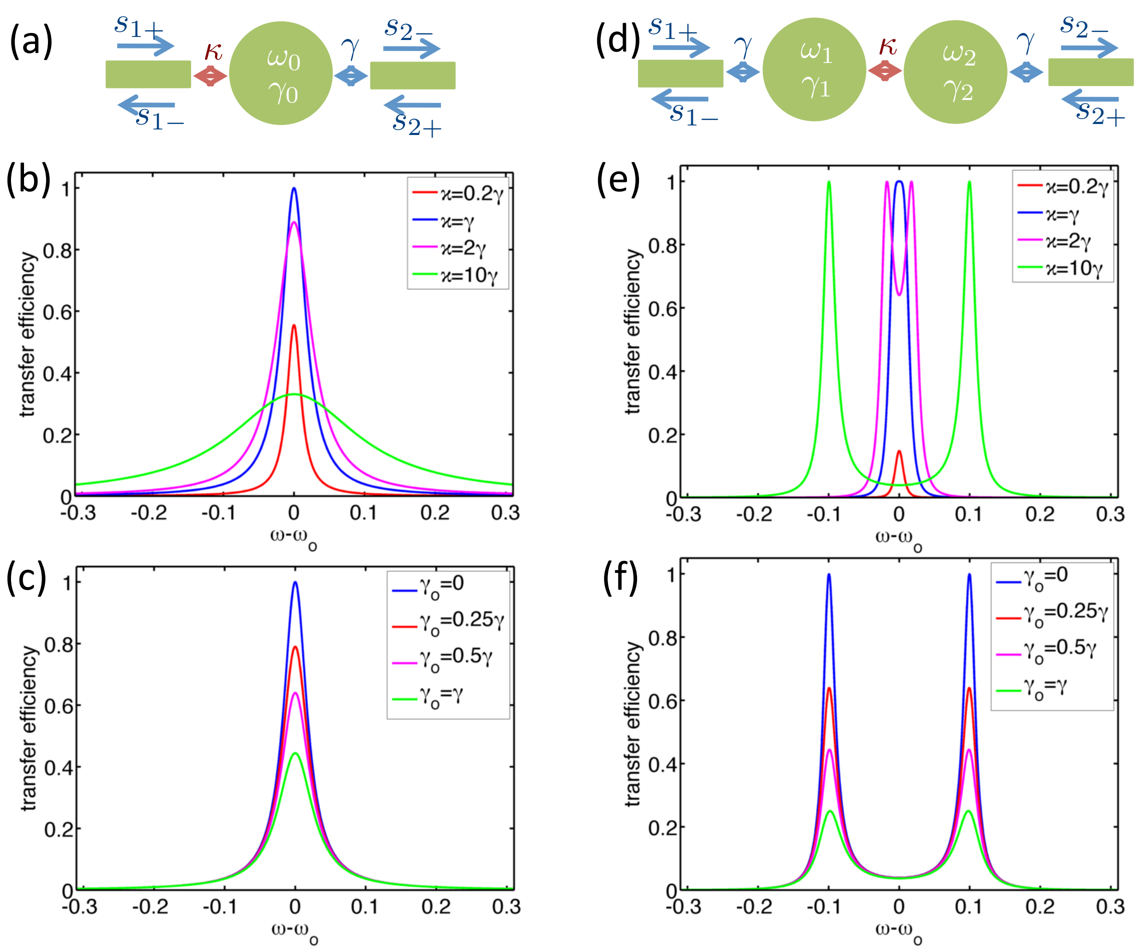

Figure 1: (a) Coupled mode theory model for the inductive power transfer system. The red arrow represents the coupling constant of the wireless power transfer. (b) Transfer efficiency spectrum for the model in (a), as we vary the coupling constant κ. Notice that the transfer efficiency reaches 100% only at a single κ value. (c) Transfer efficiency spectrum for the model in (a) in the presence of intrinsic loss. (d) Coupled mode theory model for the resonant power transfer system. (e) Transfer efficiency spectrum for the model in (d), for various coupling constants. Notice that the transfer efficiency reaches 100% for a range of κ values. (f) Transfer efficiency spectrum for the model in (d) in the presence of intrinsic loss.

Fig. 1b and Fig. 1d are the transfer efficiency spectra for the inductive and resonant inductive power transfer schemes when the intrinsic loss of the resonators is absent (i.e. $\gamma_1 = \gamma_2 = \gamma_0 = 0$). In the inductive power transfer approach, as shown in Fig. 1b, 100% transfer efficiency only occurs at the critical coupling, when both $\omega = \omega_0$ and $\kappa = \gamma$ are satisfied. As long as the operating frequency and the coupling coefficient deviates away from the critical value, the transfer efficiency drops significantly. Thus, the conventional inductive power transfer scheme reaches 100% transfer efficiency only at a single value of coupling constant, and has little tolerance for fluctuations in the coupling coefficient (or the transfer distance). In contrast, in the resonant inductive power transfer scheme, as shown in Fig. 1e, there is always a frequency, where 100% power transfer takes place, as long as one is in the strong coupling regime where the coupling coefficient characterizing the wireless power transfer (κ) dominates the output coupling rate of the resonator (γ). Therefore, compared with the conventional inductive power transfer scheme, the resonant power transfer scheme has far better distance tolerance, since 100% transfer efficiency is always reached provided that one is in the strong coupling regime.

In practice, the transfer efficiency is also limited by the intrinsic loss for both transfer schemes. Fig. 1c and f are plots of the efficiency spectra as the intrinsic loss (γ_0) varies. If all the resonators are identical, since the resonant power transfer scheme uses an additional resonator, the effect of intrinsic loss doubles and the transfer efficiency suffers twice as much from the same intrinsic loss rate as the inductive power transfer approach. Thus in general, the resonant inductive transfer scheme requires resonators with high quality factors. In addition, in the resonant power transfer scheme, it is important to maintain the symmetry between the source and the receiving resonators.

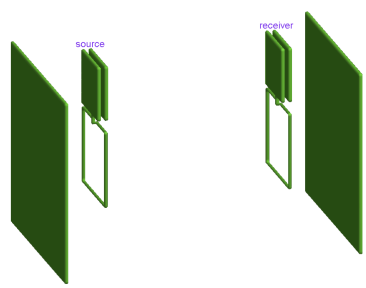

Figure 2: Optimal wireless power transfer system with close proximities of metallic planes.

We have also developed an optimal geometry for power transfer to a receiver in the vicinity of a metallic ground plane. The key idea is to place a metallic ground plane in the vicinity of the source ground plane, and to use a "twisted" resonant circuit, which are specifically tailored to the near-field electromagnetic environment of the metallic ground plane (Fig. 2). For this unique optimized geometry (Fig. 2), the full-field threedimensional simulations have demonstrated an efficiency exceeding 97%, when the two resonators are separated by a distance of two meters, with an operating frequency of 20MHz. These results have recently been published in Applied Physics Letters[17], and a patent application has been filed based on this work[18].

Figure 3: Photo of our wireless power transfer system.

Directly connected to the theoretical and computational efforts as outlined above, we undertake a set of experimental efforts towards building up our capabilities to demonstrate wireless power transfer systems with increasing complexity. We have successfully demonstrated significant wireless power transfer over a distance of 1 meter between two self-resonant coils (Fig. 3). The transferred power is sufficient to illuminate a light bulb wirelessly. Fig. 4 is our preliminary experimental result of wireless power transfer efficiencies at different transfer distance.

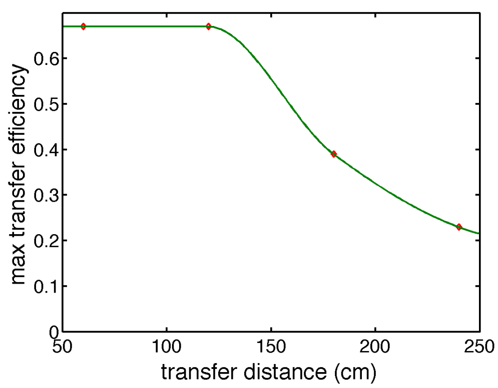

Figure 4: Experimental result of the transfer efficiencies at different transfer distance.

Progress and future plans

In the past few months, we set up both the analytical model and numerical model for the resonant inductive power transfer system. The influence of a complex electromagnetic environment to the wireless power transfer system is investigated. We have experimentally demonstrated the stationary wireless power transfer. In the future, we will continue our efforts on the optimization of the system design for better transfer efficiency and investigate dynamic charging both numerically and experimentally.

Publications:

X. Yu, S. Sandhu, S. Beiker, R. Sassoon, and S. Fan, "Wireless energy transfer with the presence of metallic planes", Applied Physics Letters 99, 214102 (2011).
U. S. Provisional Patent Application 61/542,667, filed 10/3/2011.

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