Near-field Capacitive Wireless Power Transfer Array with External Field Cancellation

Ignacio Ramos, Khurram Afridi, José A. Estrada, and Zoya Popović
Electrical, Computer and Energy Engineering
University of Colorado at Boulder
Boulder, Colorado 80309, U.S.A.
Email: ignacio.ramos@colorado.edu, khurram.afridi@colorado.edu, jose.estrada@colorado.edu, zoya@colorado.edu

***Abstract*—In this paper, a near-field phased-array cancellation technique for a modular and scalable capacitive wireless transfer system is presented. The application is for kW power transfer to static electric vehicles and vehicles in motion. The goal of the distributed array approach is to increase maximum transferable power while decreasing the external electric field produced by the WPT system, accomplished by field focusing through phase control. Full-wave simulations show that high power transfer efficiency with an accompanied 40% reduction in maximum external field can be accomplished with an 8-element array with 180° alternating phase difference between adjacent elements. A comparison is made for allocated bands at 6.78, 13.56 and 27.12 MHz showing improved focusing with increasing frequency. A system prototype at a scaled power level is currently being designed, taking account tradeoffs in circuit element loss and focusing loss.**

Keywords*—*Capacitive, Wireless Power, Electric field cancellation.

I. Introduction

Despite the progress in development of electric vehicles over the past decade, their penetration remains under 0.1 % and this is mainly due to high cost, limited range, and long charging times. Limited range and long charging times can both be traced to limitations in battery technology. One way to mitigate both problems is to reduce the on-board energy storage and deliver power wirelessly to the car. Inductive wireless power transfer (WPT) has been the main focus of research, and the majority of high-power WPT systems currently operating are inductive [1]. However, inductive powering is limited by the requirement of expensive and heavy ferrites required for cores and for external field reduction [2]. State-of-the-art inductive WPT systems achieve power densities of up to 27 kW/m^2 and efficiencies of approximately 80 % [3].

On the other hand, limited work has been done in capacitive power transfer, mostly at lower power levels and short distances, e.g. [1],[4], [5]. In [6], a capacitive wireless transfer system through the wheels of a vehicle is proposed. The system achieved a maximum power transfer of 50 W at $\approx$ 50 MHz. In [7], a high power density of 1.1 W/mm^2 is achieved at 2.6 W by WPT at 100 MHz across a 1-pF capacitance. Recently in [8], a 2.4-kW prototype was demonstrated with four 61 x 61-cm copper plates. The system achieves 90 % efficiency at 1 MHz and an air gap distance of 15 cm. In this paper, we present an array approach to capacitive wireless power transfer (CWPT) aimed at a modular and scalable system for charging electric vehicles. The work in this paper builds upon the idea presented in [9], where a new (CWPT) approach for large air-gap applications is introduced. The goal of the distributed array approach is to increase maximum transferable power while decreasing the external electric field produced by the WPT system, accomplished by field focusing through phase control. A block diagram of the array configuration is shown in Fig. 1, in which multiple conducting plates located at the bottom of the vehicle couple capacitively to multiple plates located in the road. A full-wave simulation study is carried out and the focusing effects at different frequencies and for several array configurations and relative phasing between the modules are quantified. The primary frequencies of interest are the 6.78, 13.56 and 27.12 MHz bands.

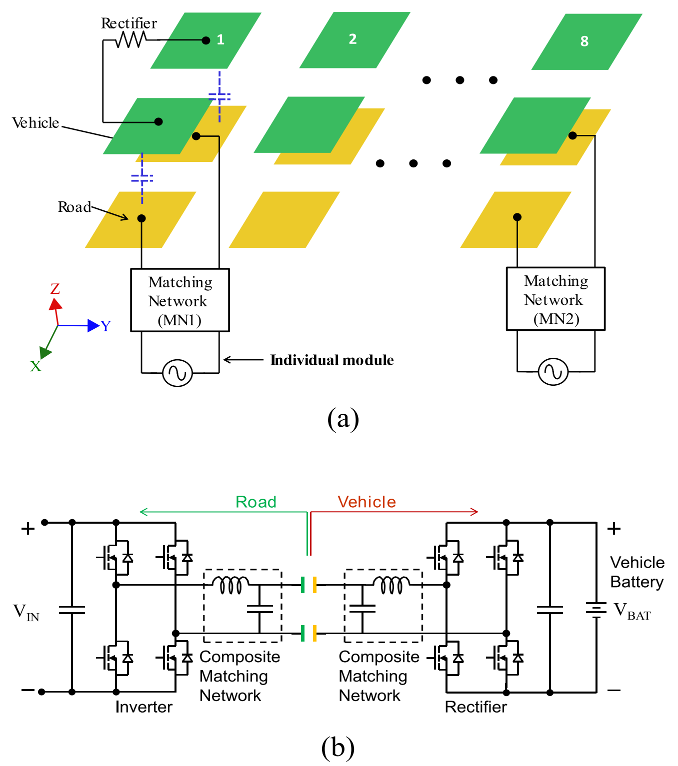

Fig. 1. (a) Block diagram of the capacitive array wireless power transfer system for a stationary vehicle. N pairs of plates are placed in the road, with inverters (dc-ac converters) connected between each pair. N identical pairs of plates are placed on the bottom of the vehicle, with rectifiers connected between the plates, closing the current loop with the plates in the ground. (b) Equivalent circuit of an individual WPT module, consisting of 4 plates, a resonant inverter and a rectifier.

II. Capacitive WPT Array Configuration

Referring to Fig. 1 (a), the architecture of the system is modular, with N pairs of plates placed in the road fed by resonant inverters (dc-ac converters) connected between each pair and N identical pairs of plates placed on the bottom of the vehicle, with rectifiers connected between the plates, closing the current loop with the plates in the ground. The simplified equivalent circuit for a single module is shown in Fig. 1(b). The number of modules N is scalable and in this work is varied between 2 and 8 to demonstrate the effect on electric field for a constant total power of approximately 1 kW transferred between road and vehicle.

The distance between the plates is another variable, and for the results presented in this paper it is fixed at 12 cm. The operating frequency is determined by the required power transfer through the small equivalent capacitance with a limited voltage level. Three different industrial, scientific, and medical (ISM) frequencies are considered in the initial design of the prototype: 6.78, 13.56 and 27.12 MHz. In a single plate-pair capacitive system, the maximum allowable power transfer density is limited by the fringing electric fields, which need to remain below the safety limits for human exposure to electromagnetic fields [10], [11]. We show that the modular approach with field focusing through a near-field phased array approach can substantially reduce the fringing electric fields. A full-wave electromagnetic model of the capacitive system is created in Ansys HFSS in order to determine the optimum parameters for electric field cancellation, for varying number of modules and frequency.

III. Full-Wave Electromagnetic Simulation Results

An equivalent model, representing the CWPT system is created in Ansys HFSS and is shown in Fig. 2. Initially, the effects of the road and the the car are not considered and only the plates and lumped ports representing the inverters and rectifiers are simulated. The area of each plate depends on the total number of plates for a fixed power level. Due to current practical restrictions, the total area occupied by the plates is limited to 200 cm^2, and the plates are modeled as 1 oz copper ($\approx$ 0.0347 mm thick). The distance between adjacent modules d_1 and the distance between positive (+) and negative (-) plates d_2, are adjusted to minimize fringing electric fields while keeping a high power transfer efficiency. The magnitude of the electric field is calculated in the two zones highlighted in the diagram of the model shown in Fig. 2: the energy-transfer zone and the safety zone at 25 cm away from the vehicle.

The energy-transfer zone is located 1 cm below the rectifier plates, where the electric field is expected to be very high and is used to estimate the transferred power. The safety zone, where the magnitude of the electric field needs to be below the safety exposure limit for humans, is located 25 cm in the x direction from the inverter plates. The electric field is calculated along the y-axis, which is the orientation along the vehicle body. The inverters are modeled as lumped ports with an impedance of 121.8 kΩ, corresponding to inverter modules with an output voltage of 4010 V and and output power of 132 W. The rectifiers are modeled as lumped ports with and equivalent impedance of 2.6 kΩ.

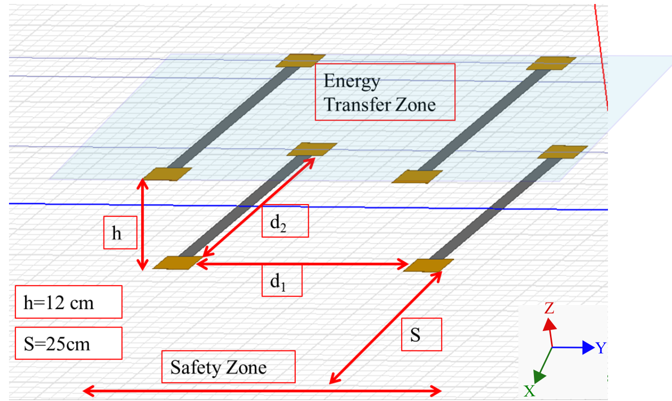

Fig. 2. Electromagnetic model used for simulations. The two zones where the magnitude of the electric field is calculated for the remaining plots in the paper are labeled as the energy-transfer zone between the plates for $(-d_2/2 < x < d/2, z = 1\,\mathrm{cm})$, and the safety zone outside of the vehicle for $x = S = 25\,\mathrm{cm}$.

Simulations were performed for $N = 2, 4, 5, 8$ modules, with $\mathrm{d}_1 = 30\,\mathrm{cm}$ and $\mathrm{d}_2 = 40\,\mathrm{cm}$. The area of the plates and the power of each inverter module is adjusted to achieve the maximum total area of 200 cm^2 and a total power of 1.12 kW. For example, the two-module simulation contains 4 plates with a 50 cm^2 area and two inverter ports fed by 560 W from 28.7 kΩ impedances.

Fig. 3 shows the simulated magnitude of the electric field as a function of normalized distance in energy-transfer zone (a) and the safety zone plane (b) for the two-module case. The dashed lines correspond to the simulation results when the inverter modules are in phase, while the solid lines shows the results for the two modules 180° out of phase. It can be observed that the phase difference between the plates causes approximately a 83 % field reduction of the fringing field at the safety zone plane at 6.78 MHz. Higher frequencies also experience a reduction of the E-field, however the effect decreases with frequency for a constant $\mathrm{d}_1 = 30\,\mathrm{cm}$.

The addition of more modules further reduces the fringing E-field in the safety zone plane. Fig. 4 shows the simulated E-field for a 8-module system in the energy-transfer and safety zones. The phase alternates 180° between adjacent modules. The field reduction in the safety zone with 8 modules is approximately 40 %. It is important to note that, as shown in Fig. 4 (a), the magnitude of the E-field in the energy-transfer zone also decreases with alternating phase between adjacent modules, which could impact the overall efficiency of the CWPT system and needs to be quantified.

In order to determine if the 180 ° alternating phase shift accomplishes the highest field cancellation, the 8-module system is simulated with different alternating phases at 6.78 MHz. Fig. 5 shows the E-field as a function of normalized distance for alternating 0 °, 45 °, 90 °, 135 °, and 180 ° phases between adjacent modules. As expected, the magnitude of the E-field decreases in both the energy-transfer and safety zones as the phase difference between adjacent modules increases. Simulations show that a 180° phase difference does indeed results in maximum E-field cancellation at the safety zone with an approximately 40 % field reduction.

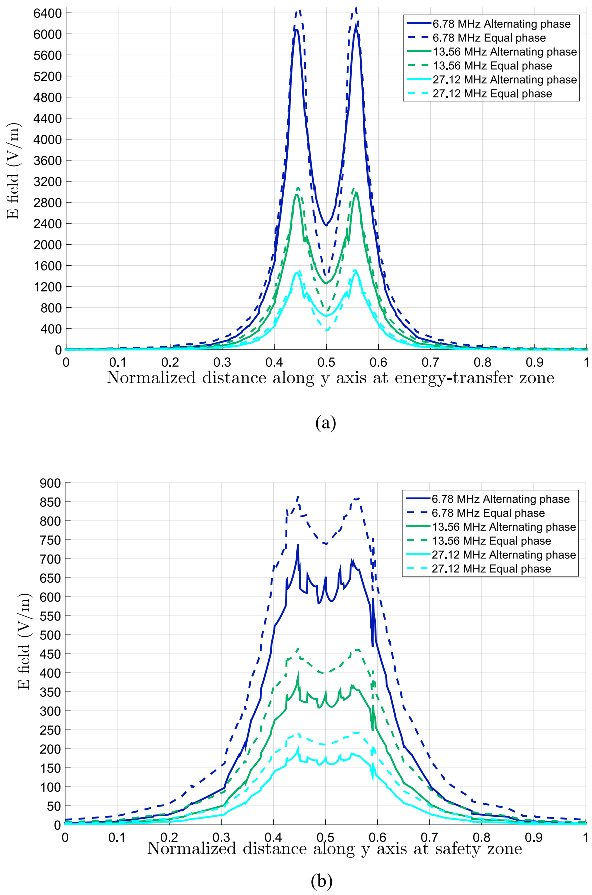

Fig. 3. Magnitude of the electric field calculated in the energy-transfer zone (a) and the safety zone (b) for a two-module array at three ISM-band frequencies under consideration. Dashed lines show the E-field with inverter modules in phase, while the solid line shows the E-field with modules having alternating 180° phases.

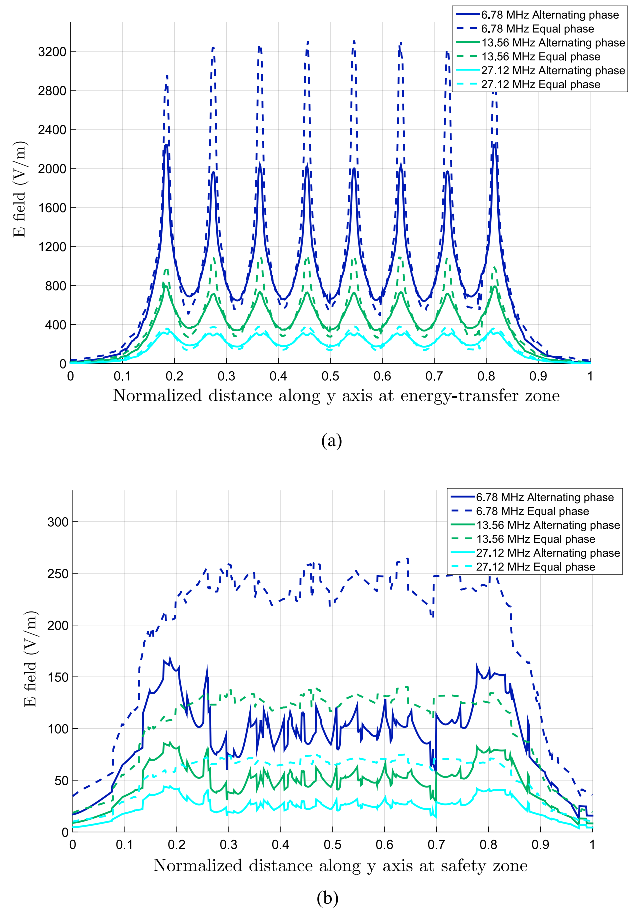

Fig. 4. Magnitude of the electric field calculated in the energy-transfer zone (a) and safety zone (b) for a 8-module array at three frequencies. Dashed lines show the E-field with inverter modules in phase, while the solid lines show the E-field with modules having alternating 180° phases.

IV. Conclusion

The simulation results shown in this paper demonstrate that capacitive power transfer lends itself to an array approach which allows for control of fringing fields for a given power level. A field reduction of approximately 40 % can be achieved with a 8-module system and a 180° alternating phase difference between adjacent modules. A prototype of the system is currently under construction, including inverter and rectifier matching circuits with inductors optimized for efficiency. The approach is scalable along many variables, and further results with the presence of the vehicle and the road, as well as varying the plate shape and separation will be presented in a follow-up paper.

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References

[1] D. Jiejian, and D.C. Ludois,“A Survey of Wireless Power Transfer and a Critical Comparison of Inductive and Capacitive Coupling for Small Gap Applications,” *IEEE Transactions on Power Electronics*, vol. 30,no. 11, pp.6017-6029, November 2015.

[2] G.A. Covic and J.T. Boys,“Modern Trends in Inductive Power Transfer for Transportation Applications,” IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 1, no. 1, pp. 28-41, March 2013.

[3] C.T. Rim, “The Development and Deployment of On-Line Electric Vehicles (OLEV)”, *IEEE Energy Conversion Congress and Exposition (ECCE)*, Denver, CO, September 2013.

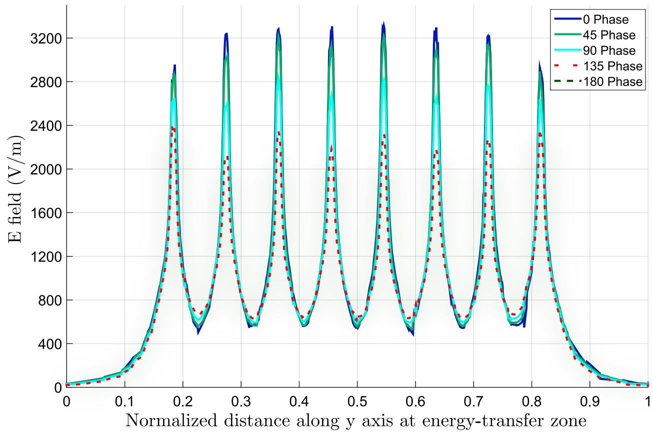
[4] R. D. Fernandes, J.N. Matos, N.B. Carvalho, ”Resonant Electrical Coupling: Circuit Model and First Experimental Results,” *IEEE Trans. Microwave Theory and Techniques*, pp. 856-859, May 2010.

[5] M. Kline, I. Izyumin, B. Boser, and S. Sanders, “Capacitive Power Transfer for Contactless Charging,” *Proceedings of the IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 1398-1404, Fort Worth, TX, March 2011.

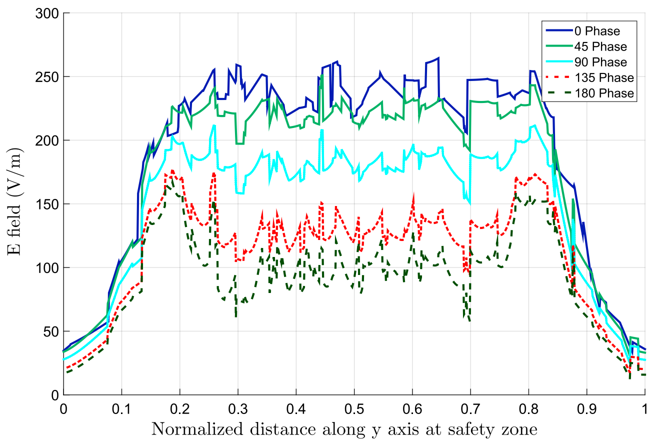
[6] T. Ohira, “Via-Wheel Power Transfer to Vehicles in Motion,”*2013 IEEE Wireless Power Transfer (WPT)*, pp.242-246, May 2013.

[7] A. Sepahvand, A. Kumar, K. Afridi, and D. Maksimovic, “High Power Transfer Density and High Efficiency 100 MHz Capacitive Wireless Power Transfer System,” *IEEE 2015 16th Workshop on Control and Modeling for Power Electronics (COMPEL)*, pp.1-4, July 2015.

[8] F. Lu, H. Zhang, H. Hofmann, and C. Mi, “A double-Sided LCLC-Compensated Capacitive Power Transfer System for Electric Vehicle



(a)



(b)

Fig. 5. Magnitude of electric field as a function of normalized distance along the body of the car at 6.78 MHz in the energy-transfer zone (a) and safety zone (b) for different alternating phases between modules.

Charging" *IEEE Transactions on Power Electronics*, vol. 63,no. 9, pp.2983-2990, September 2015.

[9] A.Kumar, S. Pervaiz, C. Chieh-Kai, S.Korhummel, Z.Popovic, and K.K. Afridi, "Investigation of power transfer density enhancement in large air-gap capacitive wireless power transfer systems," *2015 IEEE Wireless Power Transfer Conference (WPTC)*, pp.1-4, May 2015

[10] IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 KHz to 300 GHz, IEEE Standard C95.1, 1999.

[11] International Commission on Non-Ionizing Radiation Protection, "ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (up to 300 GHz)".