High-Performance Capacitive Wireless Power Transfer System for Electric Vehicle Charging with Enhanced Coupling Plate Design

Brandon Regensburger, Jose Estrada, Ashish Kumar, Sreyam Sinha, Zoya Popović and Khurram K. Afridi
Department of Electrical, Computer, and Energy Engineering
University of Colorado Boulder
Boulder, United States of America
brandon.regensburger@colorado.edu, khurram.afridi@colorado.edu

Abstract*—This paper presents a capacitive wireless power transfer system for electric vehicle charging that achieves high efficiency and record-breaking power transfer density. This high performance is enabled by multi-MHz operation, innovatively designed matching networks, and enhancements in the design of the capacitive coupling plates. The enhanced coupling plate design includes the use of circular plates enveloped in a high-breakdown-strength dielectric material. This prevents arcing and allows kilowatt-scale power transfer across large air-gaps. Multiple 6.78-MHz 12-cm air-gap prototype capacitive WPT systems are built and tested to systematically validate these coupling plate design enhancements. The first system utilizes 150-cm^2 coupling plates constructed from square-shaped bare copper sheets, and is only able to transfer 146 W at an efficiency of 84% before arcing occurs between a coupling plate and the vehicle chassis. The coupling plates are then enveloped in a thin layer of polytetrafluoroethylene (PTFE), enabling 590 W of power transfer at an efficiency of 88.4% before arcing intervenes again. The coupling plate design is then further enhanced by replacing the 150-cm^2 square plates with circular plates of the same area, also enveloped in a layer of PTFE. This system achieves a power transfer of 1125 W at an efficiency of 85%, corresponding to a power transfer density of 37.5 kW/m^2. Finally, a prototype system with 118-cm^2 PTFE-enveloped circular coupling plates is shown to transfer 1217 W at an efficiency of 74.7%; hence, achieving a power transfer density of 51.6 kW/m^2, which exceeds the state-of-the-art for large air-gap capacitive WPT systems by more than a factor of two.

Keywords—capacitive wireless power transfer; large air-gap; wireless power transfer; electric vehicle; high efficiency; high power transfer density; matching networks; high frequency; arcing

I. Introduction

Wireless power transfer (WPT) can be an effective, safe and convenient method for charging electric vehicles (EVs). WPT is also an enabling technology for driverless EVs, as it allows them to charge on their own and makes them truly autonomous. WPT for EVs can be achieved using inductively coupled coils which transfer energy through magnetic fields, or using capacitively coupled plates which transfer energy through electric fields. Inductive WPT systems need bulky and fragile ferrites for flux guidance that limit the operating frequency due to core losses, resulting in large, heavy and expensive systems, which are also difficult to embed in the roadway [1]. On the other hand, capacitive WPT systems do not require ferrites and can operate efficiently at much higher frequencies. Hence, capacitive WPT systems can be more compact, lighter, less expensive, more robust and easier to embed in the roadway. Additionally, since electric fields are inherently more directed than magnetic fields, capacitive WPT systems are more tolerant to misalignments than inductive WPT systems [2]. Large air-gap capacitive WPT systems for EV charging have been explored recently in [2]-[16], and have been shown to achieve efficiencies and power transfer densities comparable to inductive WPT systems. To further improve the power transfer densities of capacitive WPT systems for EV charging, it is necessary to evaluate and mitigate the risk of dielectric breakdown of air (i.e., arcing) that arises due to the high-strength electric fields generated during kilowatt-scale power transfer.

This paper presents a capacitive WPT system for EV charging that achieves high efficiency and very high power transfer density. This high performance is achieved through a combination of high-frequency operation, innovative matching network design, and enhancements in coupling plate design that alleviate the risk of arcing and enable kilowatt-scale power transfer across large air-gaps. The enhancements include eliminating corners from the coupling plates, and enveloping the plates with a high-breakdown-strength dielectric material. A series of 6.78-MHz 12-cm air-gap prototype capacitive WPT systems are built and tested to systematically validate these coupling plate design enhancements. The first design utilizes 150-cm^2 bare-copper square-shaped coupling plates, and transfers 146 W at an efficiency of 84%, achieving a power transfer density of 4.9 kW/m^2 before further increase in power transfer is prohibited by arcing between a coupling plate and the vehicle chassis. In the next design, the coupling plates are enveloped in a thin-layer of polytetrafluoroethylene (PTFE). This system is able to transfer 590 W at an efficiency of 88.4%, achieving a power transfer density of 19.7 kW/m^2 before arcing occurs again. As a further enhancement, the square plates are replaced with circular plates having the same 150-cm^2 area, and also enveloped in PTFE. This circular-plate system transfers up to 1125 W at an efficiency of 85%, achieving a record-breaking power transfer density of 37.5 kW/m^2. This system also achieves a peak efficiency of 89.4% at 700 W of power transfer. Finally,

978-1-4799-7312-5/18/$31.00 ©2018 IEEE

to push power transfer density even higher, the surface area of the PTFE-enveloped circular coupling plates is decreased to 118 cm^2. This system transfers 1217 W at an efficiency of 74.7%, achieving a power transfer density of 51.6 kW/m^2, which to the authors' best knowledge is more than twice the power transfer density of any reported large air-gap capacitive WPT system [12].

II. Capacitive WPT Architecture

The architecture of a capacitive WPT system for EV charging is shown in Fig. 1. This system achieves wireless power transfer using two pairs of conducting plates, one pair embedded in the road and the other attached to the underside of the vehicle chassis, with the two pairs separated by a large air-gap. An inverter converts the dc input voltage into high-frequency ac, which is fed into a resonant matching network that steps up the voltage. This creates a high voltage at the road side of the coupling plates, enabling high power transfer with low displacement currents, and thus relatively low fringing fields. On the vehicle side of the coupling plates is a second resonant matching network that steps the current up (and the voltage down) to the level required to charge the EV battery. Furthermore, both of the matching networks provide reactive compensation for the coupling plates' capacitive reactance. Finally, a high-frequency rectifier interfaces the system to the EV's battery.

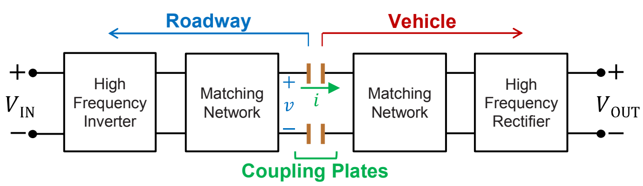


Fig. 1: Architecture of a large air-gap capacitive WPT system suitable for EV charging applications. The system comprises two pairs of coupling plates, a high-frequency inverter and rectifier, and matching networks that provide voltage or current gain and reactive compensation.

III. System Design and Optimization

An example implementation of the capacitive WPT architecture of Fig. 1 is shown in Fig. 2. It comprises a full-bridge inverter, L-section matching networks that provide the required gains and compensation, and a full-bridge rectifier. In an actual EV charging scenario, several parasitic capacitances exist in addition to the coupling capacitance C_{plate} shown in Fig. 2. The physical manifestation of the parasitic capacitances is illustrated in Fig. 3. These parasitic capacitances can severely degrade power transfer and efficiency, and hence must factor in the design of the system. A circuit schematic of the capacitive WPT system incorporating these capacitances is shown in Fig. 4(a). In this work, these parasitic capacitances are absorbed into

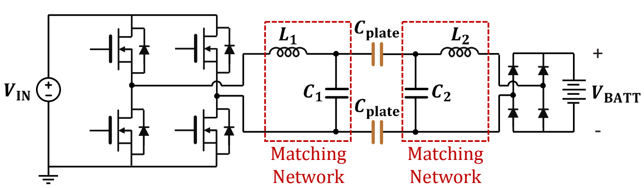


Fig. 2: Example implementation of the capacitive WPT system of Fig. 1.

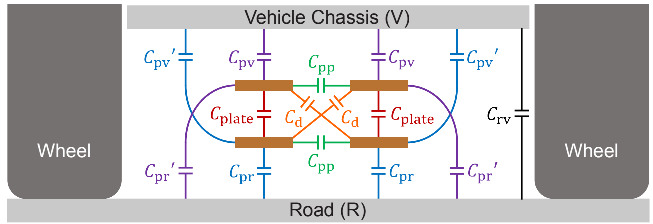


Fig. 3: Coupling plate and parasitic capacitances in an actual EV charging environment.

the matching networks of the system. This is accomplished by splitting the matching network inductors into two equal halves, one placed in the forward path and the other in the return path. The resultant circuit symmetry enforces zero volts across the vehicle-to-road capacitance C_{rv}, the ground-to-road capacitance C_{rgnd} and the ground to vehicle capacitance C_{vgnd}, eliminating their effect. The equivalent circuit model arising from the symmetrically split inductor design can be seen in Fig. 4(b). The remaining capacitive network can then be reduced to a 6-capacitance network through series and parallel combinations of the parasitic capacitances, and can be further modeled as 4-capacitance network using two-port network theory, as shown in Fig. 4(c). In this system, $C_s\left(= C_{plate} - C_d\right)$ is the equivalent series capacitance, and the parallel capacitances $C_{p1}\left(= C_{pp} + \frac{C_{pr}}{2} + \frac{C_{pv}'}{2} + C_d\right)$ and $C_{p2}\left(= C_{pp} + \frac{C_{pv}}{2} + \frac{C_{pr}'}{2} + C_d\right)$, which arise from the parasitic capacitances, are used to entirely realize the matching network capacitances. This eliminates the need for discrete capacitors that are prone to dielectric breakdown, and enables the parasitic capacitances to enhance, rather than degrade, power transfer. The L-section matching networks of the capacitive WPT system of Fig. 4(c) are designed using the optimization methodology described in [7].

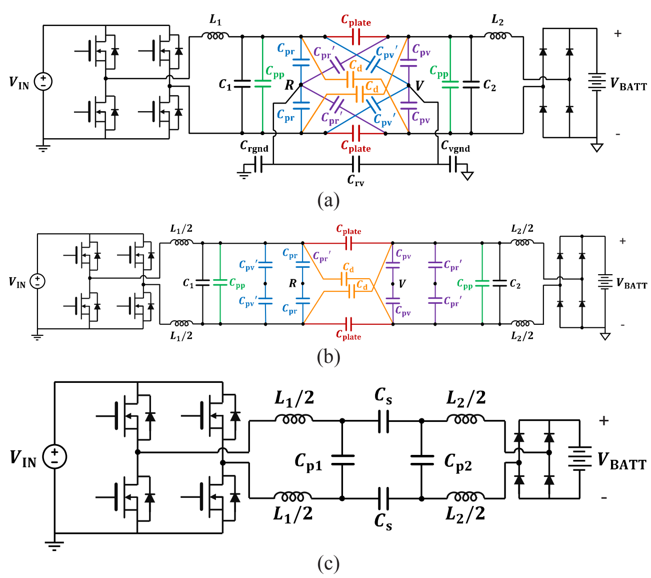


Fig. 4: Circuit schematic of the capacitive WPT system: (a) incorporating parasitic capacitances where nodes V and R represent the vehicle chassis and road respectively, (b) equivalent circuit model arising from symmetrically splitting the inductors, and (c) with parasitic capacitances comprising the matching network capacitances.

IV. Coupling Plate Design Enhancements

A major challenge in achieving high power transfer levels in capacitive WPT systems for EV charging is the risk of arcing due to the high voltages created between the coupling plates and the vehicle chassis, and the coupling plates and the roadway. Arcing creates a short circuit through the air which causes a drift between the system resonant and operating frequencies, leading to system failure and potential component damage. An effective approach to alleviating the risk of arcing is to envelope the coupling plates in a material that has high dielectric breakdown strength. In this work, PTFE, also known as Teflon, is chosen for its high dielectric strength of >20 MV/m (which is more than six times higher than that of air), and for its low dissipation factor at MHz frequencies [17]. Photographs of a square-shaped coupling plate enveloped in a layer of PTFE are shown in Fig. 5. Since PTFE has a dielectric constant of 2.1, and it completely covers one side of the coupling plate (see Fig. 5(a)), adding the PTFE envelope may significantly change the capacitance between the coupling plate and the vehicle-chassis, and between the coupling plate and the roadway. This capacitance contributes a major fraction of the matching network capacitances C_{p1} and C_{p2} in the capacitive WPT system of Fig. 4(c). Since the matching networks provide relatively large gain, they have relatively high loaded quality factors and are sensitive to changes in component values. Therefore, it is important that the change in capacitance caused by the PTFE envelope is quantified. Figure 6 shows the variation in the matching network capacitances C_{p1} and C_{p2} as a function of the thickness of the PTFE layer used to cover the coupling plates for an example 1200-W capacitive WPT system. It can be seen that for PTFE thicknesses less than 500 µm, the capacitances C_{p1} and C_{p2} change by less than 5% compared to their value without PTFE. For the prototype capacitive WPT systems described in the next section, a 254-µm thick layer of PTFE is utilized (the red circular marker in Fig. 6), which changes the capacitances C_{p1} and C_{p2} by only 1.74%; hence, minimally impacting the electrical behavior of these systems. Note that if thicker layers of PTFE than those considered in Fig. 6 are required to prevent arcing, the change in capacitance can be more significant and must be factored into the system's design. However, the thicker the PTFE layer, the higher the associated dielectric losses.

(a) (b)

Fig. 5: Photographs of a square-shaped coupling plate enveloped in PTFE: (a) side facing the vehicle chassis/roadway, and (b) side facing the other pair of coupling plates across the air gap.

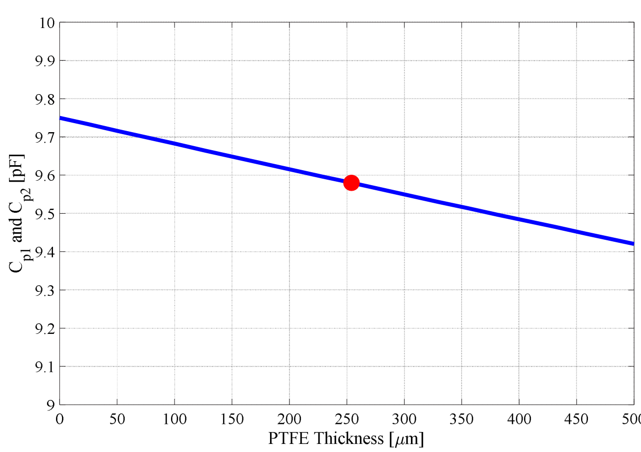


Fig. 6: The matching network capacitances C_{p1} and C_{p2} as a function of the thickness of the PTFE layer used to envelope the coupling plates. The red circular marker indicates the thickness of the 254-µm PTFE layer used in the prototype capacitive WPT systems.

To demonstrate the benefits of utilizing PTFE, an Ansys HFSS model of 150-cm^2 square-shaped coupling plates is created, as shown in Fig. 7. Simulations are performed to obtain the electric field strength in the vicinity of the plates at excitation levels corresponding to 1200 W of power transfer, both for bare copper plates and for plates enveloped in PTFE. Figure 8(a) shows a zoomed-in side-view of one of the bare copper plates. It can be seen that near the corner of the plate, where the concentration of electric charge is maximum, the field strength exceeds 3 MV/m (as indicated by the red portion of the scale); hence, resulting in the dielectric breakdown of air. A similar view of the plate when enveloped in 254-µm of PTFE is shown in Fig. 8(b). The maximum field strength near the corner of the plate is now reduced 2.4 MV/m (yellow portion of the scale), enabling higher power transfer levels before arcing.

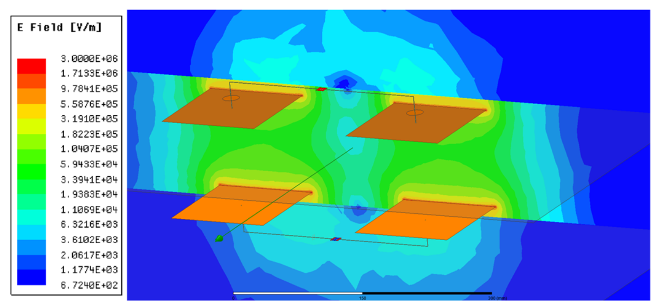
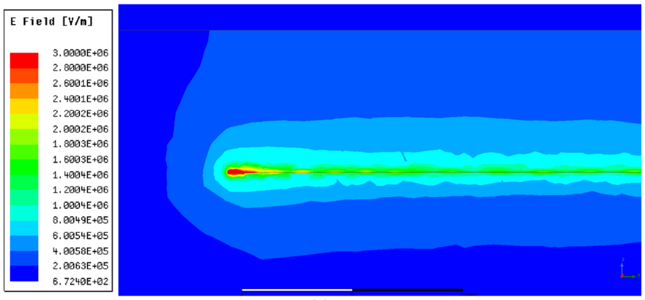
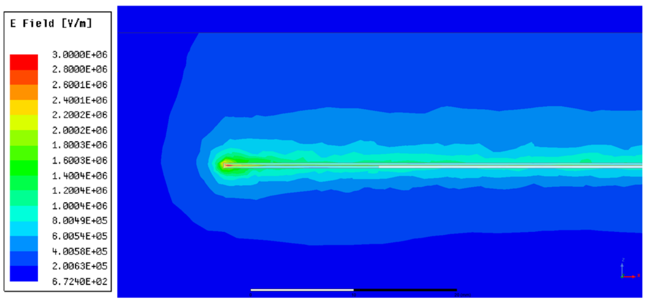


Fig. 7: Field plot of square coupling plates. A model is also created for circular coupling plates.

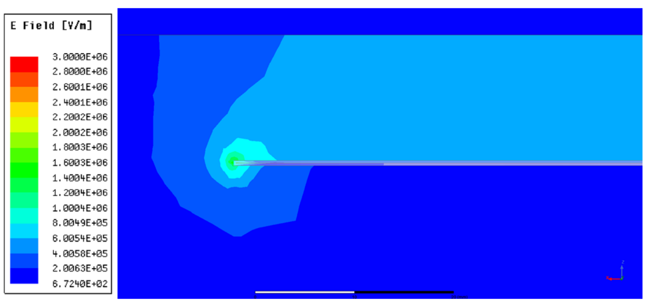
As discussed above, the electric field strength, and hence, the risk of arcing is highest near the corner of the coupling plates, both with and without PTFE (see Fig. 8(a) and (b)). Therefore, arcing is most likely to occur at these corners (which is also experimentally validated later). To further alleviate arcing and achieve even higher power transfer levels, it is preferable to utilize corner-free coupling plates – for example, elliptical or circular plates. By avoiding corners, such shapes exhibit a more even distribution of charge, and hence, lower peak electric fields in the vicinity of the plates. This has also been verified in simulation. As an example, a zoomed-in side-view of 150-cm^2 circular coupling plates enveloped in 254-µm PTFE is shown in Fig. 8(c). The edges of the plates now have a peak field strength of 1.2 MV/m (green portion of the scale). Compared to PTFE-enveloped square plates, this represents a factor-of-two reduction, and hence, proportionally higher power transfer capability.



(a)



(b)



(c)

Fig. 8: Field plots of electric field strength when the coupling plate excitation level corresponds to 1200 W of power transfer for: (a) bare-copper square plates, (b) PTFE-enveloped square plates, and (c) PTFE-enveloped circular plates.

V. Prototype Design and Experimental Results

A series of prototype 6.78-MHz 12-cm air-gap capacitive WPT systems are built and tested to validate the efficacy of the above-described coupling plate design enhancements. These prototype systems have a circuit schematic similar to that shown in Fig. 4(c), with one difference being that the rectifier and battery are emulated by a resistive load. A photograph of the prototype system with PTFE-enveloped square coupling plates is shown in Fig. 9. The large aluminum sheets visible in Fig. 9 are used to mimic the vehicle chassis and the road, and the distance between these sheets and the coupling plates (seen between the sheets) is controlled to realize the desired matching network capacitances. The inverter is constructed using 650-V

TABLE I. Select Circuit Parameters of the Prototype Capacitive WPT Systems

Plate Area [cm^2]	C_{plate} [pF]	L_1 & L_2 [µH]	C_{p1} & C_{p2} [pF]	R_{load} [Ω]
150	0.88	53	9.58	45
118	0.46	53	3.95	45

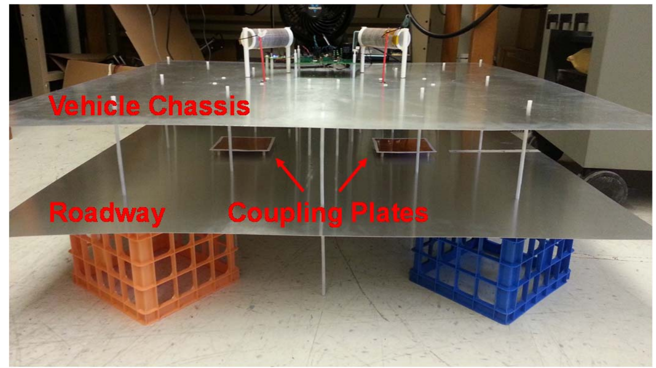


Fig. 9: Field plot of square coupling plates. A model is also created for circular coupling plates.

30-A GaN Systems GS66508T enhancement-mode GaN transistors. The matching network inductors are realized as single-layer air-core solenoids. Component details of the prototype systems is provided in Table I.

The first prototype system utilizes 150-cm^2 bare-copper 12.25-cm × 12.25-cm square coupling plates. This design transfers up to 146 W at an efficiency of 84%, achieving a power transfer density of 4.9 kW/m^2 before arcing occurs between the corners of the coupling plates and the aluminum sheet modeling the vehicle chassis, as shown in Fig. 10. The square coupling plates are then enveloped in a 254-µm thick layer of PTFE. This design transfers up to 590 W at an efficiency of 88.4%, achieving a power transfer density of 19.7 kW/m^2 before arcing occurs again. Next, the square coupling plates are replaced by circular coupling plates having the same 150-cm^2 area (13.8-cm diameter), also enveloped in a 254-µm thick layer of PTFE, as shown in Fig. 11. This design transfers up to 1125 W at an efficiency of 85%, achieving a record power transfer density of

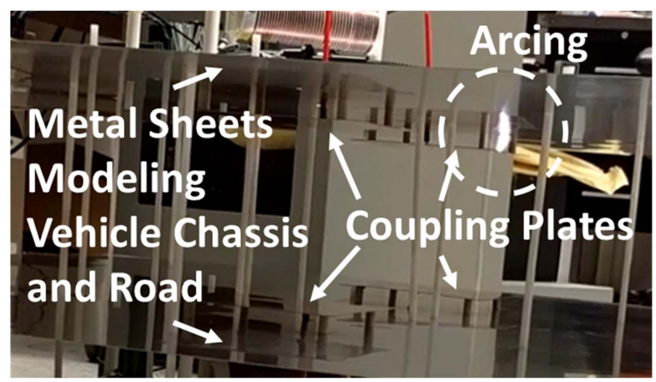
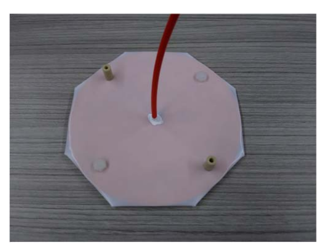


Fig. 10: Photograph of the dielectric breakdown of air (i.e., arcing), between the coupling plates and the vehicle chassis.



(a)

(b)

Fig. 11: Photographs of a circular-shaped coupling plate enveloped in PTFE: (a) side facing the vehicle chassis/roadway, and (b) side facing the other pair of coupling plates across the air gap.

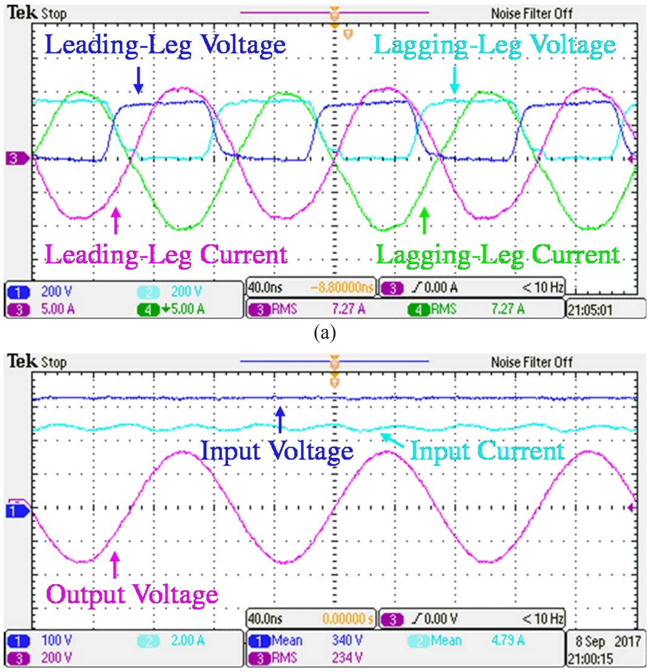


Fig. 12: Measured waveforms of the prototype WPT system operating at 1217 W: (a) inverter switch node voltages and currents operating with ZVS, and (b) system input voltage and current, and output voltage.

37.5 kW/m^2. Additionally, this circular plate design achieves a peak efficiency of 89.4% at 700 W of power transfer. To push the power transfer density even higher, a fourth coupling plate design with 118-cm^2 circular (12.25-cm diameter) coupling plates enveloped in 254-µm thick PTFE is constructed. This design operating at 7.42 MHz transfers up to 1217 W at an efficiency of 74.7%, achieving a power transfer density of 51.6 kW/m^2, which exceeds the power transfer density of any reported large air-gap capacitive WPT system by more than a factor of two [12]. Measured waveforms of the prototype system transferring 1217 W are shown in Fig. 12. It can be seen from Fig. 12(a) that the inverter operates with zero-voltage switching (ZVS). A plot of efficiency versus power transfer for all four coupling plate designs is shown in Fig. 13.

VI. Conclusions

This paper presents a very-high-power-density high-efficiency capacitive WPT system for EV charging. This high performance is enabled by multi-MHz operation, innovatively designed matching networks, and enhancements in the design of the capacitive coupling plates to alleviate the risk of arcing. These enhancements include the use of corner-free coupling plates and enveloping the plates with a high-breakdown-strength dielectric material. Prototype 6.78-MHz 12-cm air-gap capacitive WPT systems utilizing four different coupling plate designs are built and tested. The first design utilizes 150-cm^2 bare-copper square coupling plates, and transfers up to 146 W at an efficiency of 84%, achieving a power transfer density of 4.9 kW/m^2 before arcing occurs. The second design utilizes 150-cm^2 square coupling plates enveloped in a 254-µm layer of PTFE, and transfers up to 590 W at an efficiency of 88.4%, achieving a power transfer density of 19.7 kW/m^2. The third design utilizes

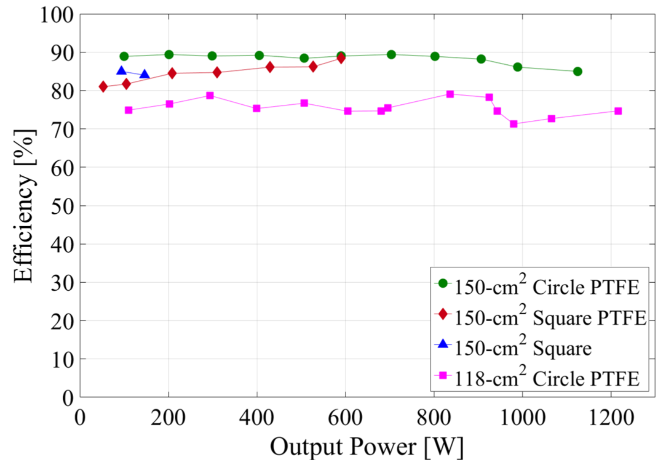


Fig. 13: Plot of efficiency versus power transfer for the prototype capacitive WPT systems utilizing: bare-copper 150-cm^2 square (blue), PTFE enveloped 150-cm^2 square plates (red), PTFE enveloped 150-cm^2 circular plates (green), and PTFE enveloped 118-cm^2 circular plates (magenta).

150-cm^2 circular coupling plates enveloped in 254-µm PTFE, and transfers up to 1125 W at an efficiency of 85%, achieving a record power transfer density of 37.5 kW/m^2. Finally, a fourth design with PTFE-enveloped circular coupling plates of a smaller area (118-cm^2) transfers up to 1217 W at an efficiency of 74.7%, achieving a power transfer density of 51.6 kW/m^2, which exceeds the power transfer density of any reported large air-gap capacitive WPT system by more than a factor of two.

References

[1] 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.

[2] F. Lu, H. Zhang and C. Mi, “A Review on the Recent Development of Capacitive Wireless Power Transfer Technology,” *Energies 2017 Special Issue on Wireless Power Transfer and Energy Harvesting Technologies*, art. 10, 1752, November 2017.

[3] A. Kumar, S. Pervaiz, C.K. Chang, S. Korhummel, Z. Popovic and K.K. Afridi, "Investigation of Power Transfer Density Enhancement in Large Air-Gap Capacitive Wireless Power Transfer Systems," *Proceedings of the IEEE Wireless Power Transfer Conference (WPTC)*, Boulder, CO, May 2015.

[4] F. Lu, H. Zhang, H. Hofmann and C. Mi, “A Double-Sided LCLC-Compensated Capacitive Power Transfer System for Electric Vehicle Charging,” *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6011-6014, November 2015.

[5] F. Lu, H. Zhang, H. Hofmann and C. Mi, “A CLLC-compensated high power and large air-gap capacitive power transfer system for electric vehicle charging applications,” *Proceedings of the IEEE Applied Power Electronics Conference and Exposition (APEC)*, Long Beach, CA, March 2016.

[6] I. Ramos, K.K. Afridi, J. A. Estrada and Z. Popović, "Near-Field Capacitive Wireless Power Transfer Array with External Field Cancellation," *Proceedings of the IEEE Wireless Power Transfer Conference (WPTC)*, Aveiro, Portugal, May 2016.

[7] S. Sinha, A. Kumar, S. Pervaiz, B. Regensburger and K.K. Afridi, "Design of Efficient Matching Networks for Capacitive Wireless Power Transfer Systems," *Proceedings of the IEEE Workshop on Control and Modeling for Power Electronics (COMPEL)*, Trondheim, Norway, June 2016.

[8] F. Lu, H. Zhang, H. Hofmann, Y. Mei and C. Mi, "A Dynamic Capacitive Power Transfer System with Reduced Power Pulsation," *Proceedings of the IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)*, Knoxville, TN, October 2016.

[9] K. Doubleday, A. Kumar, S. Sinha, B. Regensburger, S. Pervaiz and K.K. Afridi, "Design Tradeoffs in a Multi-Modular Capacitive Wireless Power Transfer System," *Proceedings of the IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)*, Knoxville, TN, October 2016.

[10] F. Lu, H. Zhang, H. Hofmann and C. Mi, "An Inductive and Capacitive Combined Wireless Power Transfer System with LC-Compensated Topology," *IEEE Transactions on Power Electronics*, vol. 31, no. 12, pp. 8471-8482, December 2016.

[11] H. Zhang, F. Lu, H. Hofmann, W. Liu and C.C. Mi, "A Four-Plate Compact Capacitive Coupler Design and LCL-Compensated Topology for Capacitive Power Transfer in Electric Vehicle Charging Application," *IEEE Transactions on Power Electronics*, vol. 31, no. 12, pp. 8541-8551, December 2016.

[12] B. Regensburger, A. Kumar, S. Sinha, K. Doubleday, S. Pervaiz, Z. Popović, K.K. Afridi, "High-Performance Large Air-Gap Capacitive Wireless Power Transfer System for Electric Vehicle Charging," *Proceedings of the IEEE Transportation Electrification Conference and Expo (ITEC)*, Chicago, IL, June 2017.

[13] K. Doubleday, A. Kumar, B. Regensburger, S. Pervaiz, S. Sinha, Z. Popovic and K.K. Afridi, "Multi-Objective Optimization of Capacitive Wireless Power Transfer Systems for Electric Vehicle Charging," *Proceedings of the IEEE Workshop on Control and Modeling for Power Electronics (COMPEL)*, Stanford, CA, July 2017.

[14] S. Sinha, B. Regensburger, K. Doubleday, A. Kumar, S. Pervaiz and K.K. Afridi, "High-Power-Transfer-Density Capacitive Wireless Power Transfer System for Electric Vehicle Charging," *Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE)*, Cincinnati, OH, October 2017.

[15] J. Estrada, S. Sinha, B. Regensburger, K.K. Afridi and Z. Popovic, "Capacitive Wireless Powering for Electric Vehicles with Near-Field Phased Arrays," *Proceedings of the European Microwave Conference*, Nuremburg, Germany, October 2017.

[16] S. Sinha, A. Kumar, B. Regensburger, and K.K. Afridi, "A Very-High-Power-Transfer-Density GaN-Based Capacitive Wireless Power Transfer System," *Proceedings of the IEEE Workshop on Wide Bandgap Power Devices and Applications (WiPDA)*, Albuquerque, NM, October/November 2017.

[17] DuPont Fluoroproducts, *Teflon PTFE Fluoropolymer Resin Properties Handbook*, 1996, p. 28.