This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMAG.2017.2654164, IEEE Transactions on Magnetics

Efficient Wireless Power Charging of Electric Vehicle by Modifying the Magnetic Characteristics of the Transmitting Medium

Mohammad Hazzaz Mahmud[1], Weam Elmahmoud[2], M.R. Barzegaran[1], Nicholas Brake[2]
[1] Department of Electrical Engineering, Lamar University
[2] Department of Civil and Environmental Engineering, Lamar University

Abstract— There is a developing enthusiasm for electric vehicle (EV) innovations because of their lower fuel utilization and greenhouse emission output. Integrating EV's with highway wireless power transfer (WPT) technology can appropriately reduce charging time and possibly expand their travel distance. There are several issues with the current WPT technology for electric vehicles: 1) low efficiency due to large coil-coil distance and 2) slow charging time. Two ideas are proposed in this paper to increase system efficiency: 1) using a modified cement for covering the transmitting antenna area, and 2) using high frequency wide band gap switches which can transfer a high amount of power in a short time. The optimization study of the receiving and transmitting coils is implemented with and without a core through 3D finite element analysis. The physics-based analysis is coupled with circuit-based analysis for utilizing high frequencies wide band gap switch (SiC MOSFET). On the material side, the electromagnetic and mechanical properties of the modified cementitious composite is characterized and the results show significant improvement in the system efficiency.

***Index Terms-* Material Modification, Wide Band Gap Switches, Wireless Power Transfer**

I. INTRODUCTION

In just over a century, the combustion engine vehicle has turned into one of the significant producers of greenhouse gasses. Plug-in Electric Vehicles (PEVs) have been projected as one of the next-generation methods of transportation and are designed to address the international environmental, energy, and sustainability grand challenges. Although there is significant incentive to use EVs, the demand is still relatively low. The major disadvantage of EVs is the inefficiency of the battery and overall power transfer mechanism. The batteries are expensive, charge relatively slowly, add to the size and weight of the vehicle, and have relatively low energy density. Moreover, long charging times and mechanical issues associated with charging cables are the primary disadvantages of present PEV technology that hinders expanded use.

The wireless power transfer (WPT) system can be utilized to remove dangerous above-ground electrical cables and is also not restricted to parking lots or stationary traffic systems. The system can be embedded within the roadway at intersections or even within a highway system with moving vehicles. For this to be feasible, the vehicle's battery must be charged quickly and efficiently while on the move. Placing this system within a non-conductive or magnetically permeable cementitious media; however, will reduce the efficiency. Efforts have been made in the past to increase energy efficiency in WPT systems specifically applied to EVs, which includes: the modification the design of coils [1], different amplification circuits in transmitting and receiving [2], applying different reconfigurable control architectures and algorithms [3], and enhancing power transfer ratio [4].

The objective of this project is to address the stated problems by first modifying the electromagnetic characteristics of the cementitious media that will be sandwiched between the transmitting and receiving coils and secondly, by using high frequency wide band gap switches.

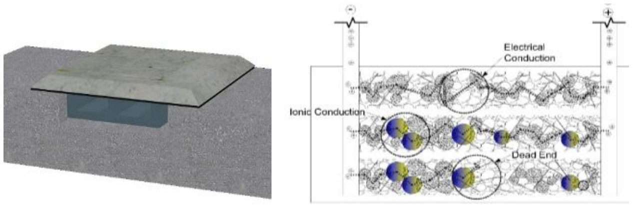
II. MODIFICATION IN MEDIUM FOR ENHANCEMENT OF POWER TRANSFER USING NANO-MAGNETICS MATERIALS

In past efforts, a large air gap between WPT coils was maintained to allow for easy transport or mobility of one or both coils. In EV applications, since the receiver is in the vehicle, having air as the medium is inevitable. However, to increase efficiency, this air gap should be reduced and partially replaced by a medium that has higher conductivity and magnetic permeability. The ground clearance must still, however, adhere to local standards. The ground clearance is defined as the amount of space between the base of an automobile tire and the underside of the chassis; or, to be more specific, the shortest distance between a flat, level surface, and any part of a vehicle other than those parts designed to contact the ground (such as tires, tracks, skis, etc.). Ground clearance is measured with standard vehicle equipment, and for cars, is usually given with no cargo or passengers. It is 100 mm in USA [3]. Hence the distance between the two coils would be around 150 mm. Having 150 mm layer of air with conductivity of 1 S/m and permeability approximately 1 H/m significantly reduces the efficiency of the WPT. In addition, simply burying the transmitting coil under a non-conductive or non-permeable roadway will also decrease efficiency. In this project, it is proposed to enhance the conductive and magnetic properties of a concrete roadway media to increase power transfer efficiency.

The electrical transport properties of a cementitious hydrated mortar are significantly influenced by porosity, pore solution, bulk resistivity of the solid phases [6], and relative humidity [7]. The bulk resistivity (ρ_b) shown in equation (1) is dependent on pore solution resistivity (ρ_0), pore volume fraction (ϕ), and the tortuosity (β) of the network [8].

$$\rho_b = \rho_0 \frac{1}{\phi\beta} = \rho_0 F \tag{1}$$

Fig. 1 shows a rendered CAD drawing of the modified pavement system and the various conduction pathways, which include: ionic conduction, and electrical conduction via the cement matrix and/or conductive fibers.



(a) (b)

Fig. 1 (a) CAD: modified road surface, (b) concrete conduction pathways

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMAG.2017.2654164, IEEE Transactions on Magnetics

III. ENHANCING BATTERY LIFETIME AND CHARGING TIME BY UTILIZING THE WBG SWITCHES

Building a bidirectional power converter that works with WBG switches, such as SiC, is proposed to improve output efficiency and increase the switching frequency to a range between 10-100 kHz. By increasing the current, switching frequencies, as well as decreasing the ripples and EMIs, the charging time would decrease.

For over three decades, power management efficiency and cost have improved steadily as innovations in MOSFET structures, technology, and circuit topologies have kept pace with the growing needs for electrical power in our daily lives. After that, Gallium Nitride (GaN) transistors have continued to make inroads in RF applications, as several other companies have entered the market. However, this technology is limited by device cost as well as the inconvenience of depletion-mode operation (normally conducting and requires a negative voltage on the gate to turn the device off). Due to advantages of silicon, which is used for switches, GaN, can be relied upon to improve output power in radar or an electric vehicle.

Our proposed circuit is modified by changing IGBT switching to SiC and GaN switching. Accordingly, the switching frequency increases and new compensation circuits in the transmitter and receiver should be determined. Thus, the charging time decreases, and number of times that the battery can be charged also increases. Fig. 2 shows the steps required to achieve this outcome.

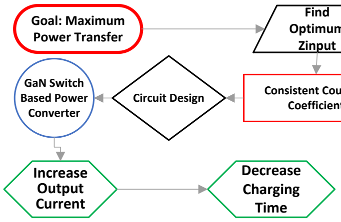


Fig. 2. Flowchart of the steps in decreasing charging time

Battery charging time depends on the system power rating. This can best be explained through an example using a system at 3.3-6.6kW. *Charge time is obtained by dividing the energy required by the amount of power transferred into the system*. At 3.3kW, the charge time would be around 6.5 hours. The charge time would be reduced to slightly over 3 hours if the power level was 6.6kW. In case of using IGBT switch, the rated energy is 60Ah based on the proposed design at an output or receiver current of 8.14A. At these levels, the charging time would be $t_{charging}=60/8.14=7.3h$. By changing IGBT switches with GaN switches, the transmitter and receiver current will increase, and reduced charging time can be achieved. Moreover, by using SiC switches, the efficiency and maximum output power transfer can be improved by increasing the switching frequency; therefore, the system has increased transmitter and receiver current as well.

There are some concerns, however, that needs to be addressed: 1) the radiated and conducted electromagnetic interference, as well as the 2) high Ldi/dt due to the increased switching frequency. To address this issue, a SiC switch is utilized for building a bidirectional converter to control the permanent magnetic synchronous machine that is considered fit for EVs. The advantages/disadvantages of SiC-MOSFET and IGBT switch are compared by quantifying the reduction of current harmonics, and the reduction of conducted electromagnetic interference associated with the control of permanent magnet synchronous motor. The common mode voltage is measured for 45 Nm reference torque with Si-IGBT and SiC-MOSFET and the results in Fig. 3 shows great improvement. This test has been done independently from other tasks of this paper to compare, explicitly, the effect of the switch. As illustrated in Fig. 3, the ripples of SiC-MOSFET are significantly reduced compared to the Si-IGBT. Both the current harmonics and conducted EMI is reduced for SiC-MOSFET. This occurs due to the high switching frequency response of SiC-MOSFET and the high-resolution control technique.

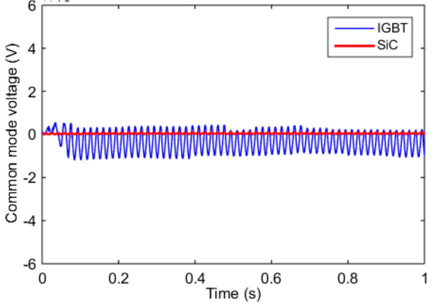
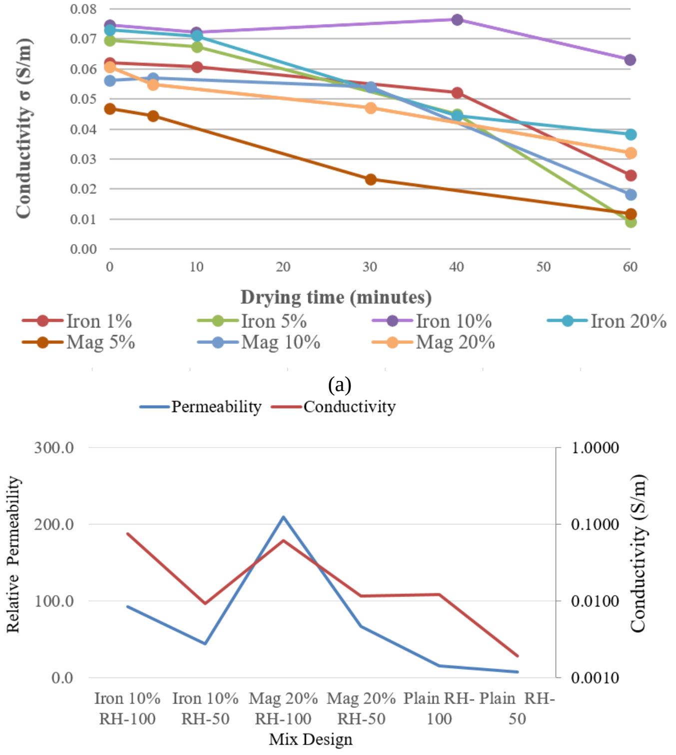


Fig. 3. Common mode voltage at the terminal of bi-directional converter

IV. EXPERIMENTAL RESULTS

The modified cementitious media was manufactured with a type I Portland cement paste and mixed with water at a water-cement ratio of 0.35, and was doped with varieties of powder, that are: Iron, and Magnetite (Mag) (@ 1%, 5%, 10%, 20% replacement by cement mass). The conductivity, and permeability of each hardened doped composite was measured for 7 days. Fig. 4 shows the conductivity and relative permeability at 5 kHz.



(a)

(b)

Fig. 4. Material test result (a) Conductivity and (b) Permeability at 5kHz

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMAG.2017.2654164, IEEE Transactions on Magnetics

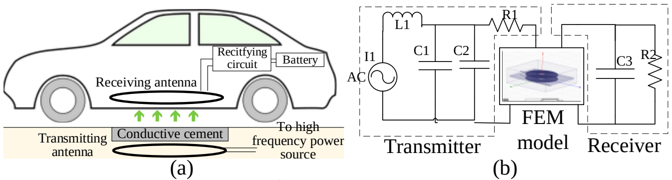
The results indicate that a 10% iron and 20% magnetite dosages produces the greatest permeability. This is sensible because at this dosage, the eddy losses are most likely kept at a minimum. The 10% iron and 20% magnetite mix were then tested under compression (ASTM C109 [9]) and found to yield a strength of 74 ± 12% MPa for the 10% iron and 59 ± 16% MPa for the 20% magnetite at 28 days. The setting time was measured using ASTM C807 [10] and found to have a final set of 250 minutes. The test setups are shown in Fig. 5.


(a) (b)

Fig. 5. The material experiment test setup (a) compression, (b) setting

V. MODEL DESIGN AND DISCUSSION

The WPT working prototype and circuit schematic are shown in Fig. 6(a) and Fig 6(b). A 3D finite element model is solved in real-time with the circuit software to study the power transfer efficiency.



(a) (b)

Fig. 6 (a) Prototype of the setup, (b) circuit representation

Both maximum power transfer operation and maximum efficiency condition are design goals. Two loops composed of a transmitter and receiver are used for wireless power transfer. The design is based on 3D physics-based analysis using finite element through Magsoft Flux. The initial goal was to simulate the power transfer between a pair of transmitting and receiving coil configurations and coupling the FEM model with Matlab. This coupling allows the model to be tested in a real circuit. The first step was to design two coils at an optimized clearance within the standard range. The transmitting and receiving coil have identical polygon helix geometry, which has been recommended in previous efforts [3]. The coil has a 15cm diameter with a 2mm thickness.

To enhance the electromagnetic mutuality between the transmitter and receiver, an iron core is incorporated within the transmitting and receiving coils. The properties of core material are shown in Table I. Fig. 7 shows the coils with cores and associated dimensions with the modified cementitious media in between the core and coils.

Table I. Properties of Core Material

Name	Value	Unites
Relative Permeability	4000	
Bulk Conductivity	1	Siemens/m
Mass Density	7870	w/m^3

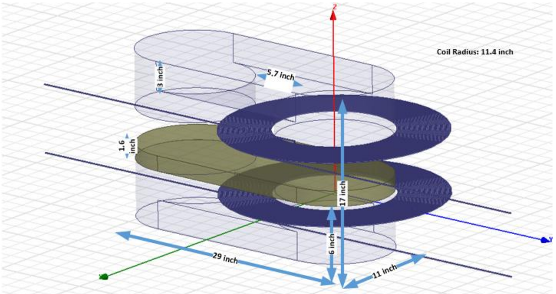
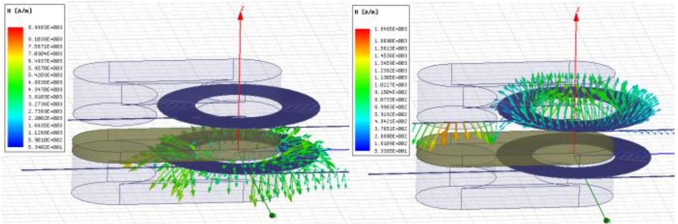


Fig. 7. Prototype of the transmitting and receiving system with modified medium and core

The properties of the modified medium with 20% magnetite are shown in Table II.

Table II. Properties of Medium

Name	Value	Units
Relative Permeability	150	
Bulk Conductivity	0.1	Siemens/m



(a) (b)

Fig. 8 (a) H-field vector of transmitter. (b) H-field vector of receiver

Fig. 8 shows the 3D H-field results for the transmitter and receiver coil geometry design. This is the result with 15A input current to the coil of transmitter. The H-field appears to be symmetric around the coil and core. Since the material in between is not air, the H-field for such a low frequency scattering incident is derived through the lossy medium equation [5]:

$$\mathbf{E} = \left(A_x e^{j\delta x} \hat{x} + A_y e^{j\delta y} \hat{y} \right) e^{-jkz}, \quad \mathbf{H} = Y\hat{k} \times \mathbf{E} \tag{1}$$

For a lossy medium, the permittivity and/or permeability may be complex and hence the wavenumber *k* is expressed as:

$$k = \omega\sqrt{\mu\varepsilon} = \omega\sqrt{\mu'\varepsilon'\left(1 - j\tan\delta\right)} \tag{2}$$

$$\psi = e^{-jk\hat{k}\bullet r} = e^{-k_2\hat{k}\bullet r} e^{-jk_1\hat{k}\bullet r} \tag{3}$$

where *Ax*, *Ay*, δx and δy are real. They represent the magnitude and phase of the electric field components in the transverse plane and ψ and *Y* are the field and the intrinsic admittance.

The magnetic field of transmitter (Tx) and receiver (Rx) core are shown in Fig. 9. As shown, there is no H-field spectrum in the area other than core region which signifies negligible magnetic field dispersion and dramatically higher magnetic field intensity.

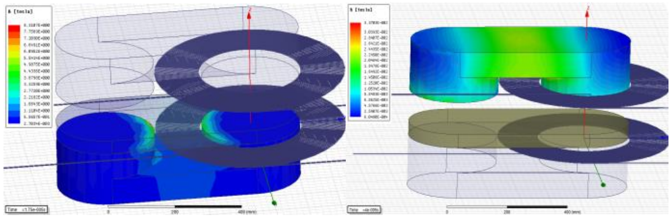

(a) (b)

Fig. 9 (a) Magnetic field of Tx core. (b) Magnetic field of Rx core

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMAG.2017.2654164, IEEE Transactions on Magnetics

As discussed in section 2, the core is buried under the ground with the transmitting system. While the above ground clearance is still air, having this modified medium partially replaces some of the air ground clearance, amplifies the field and reduces power loss. The magnetic field of the modified medium in between two cores is shown in Fig. 10. As shown, the scattered fields are not visible at the interface of the core and modified media which signifies appropriate and adequate permeability.

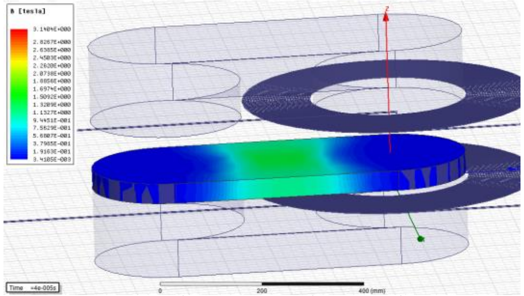


Fig. 10. Magnetic field strength of the modified medium

Before measuring the efficiency of the holistically modified WPT system, it must be confirmed that the circuit is carefully tuned to a resonant frequency of 50 kHz, so the reflected impedance at the transmitting terminal will be purely resistance. For this purpose, it is necessary to adjust the tunable capacitor carefully to make the two coils resonate at the same frequency. Parameters of each individual circuit elements based on the circuit in Fig 6(b) are shown in Table III. Source parameters are the following: Current Source: 15A and input frequency: 50 kHz.

Table III. Simulation Circuit Parameters

Transmitter		Receiver	
Parameter	Value	Parameter	Value
C1	470pf	C2	470pf
R2	100 ohms	R1	10 ohms
Inductance	41.76658mH	Inductance	2.571544mH
Mutual Inductance: 1.382148mH			

To validate this configuration, a circuit has been designed with the necessary components shown in Fig. 6(b). The results in Fig. 11 show that the output current is almost 13A at a 15A input current. An 86% power transfer efficiency was achieved in terms of input and output.

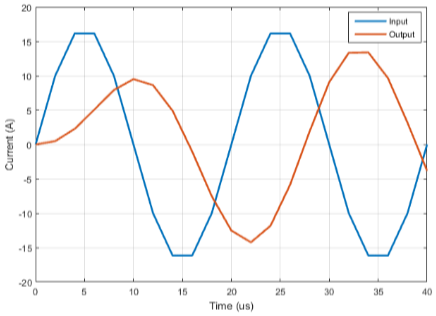
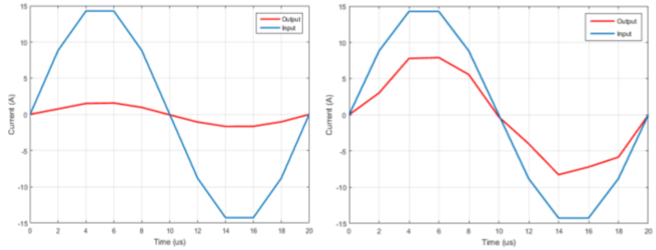


Fig .11. Output current using the model with core and the modified medium.

To test the effects of the modified medium, a system with and without a core and modified media were studied. Using the defined configuration and circuit parameters, the output current reduced to 2A from 13A, which is significantly lower. The output waveform is shown in Fig. 12(a) without the modified medium. Fig. 12(b) shows the output waveform of the same model but, this time using the modified medium with 10% Iron. This figure shows the necessity of using the modified cementitious medium. The voltage comparison would be relevant to the mutuality as well as transmitter current as V_R: $j\omega \cdot M \cdot It$.



(a) (b)

Fig. 12. Receiving current using the model without core and (a) without the modified medium. (b) with the modified medium

VI. CONCLUSION

Enhancing the magnetic mutuality between the two coils in a wireless power transfer systems was proposed to significantly reduce charging time of an electric vehicle (EV). Improved power efficiency decreases charging time and will lead to more robust and reliable EV charging mechanisms. The proposed system, which uses an ensemble of modified components: modified pavement media, and high frequency wide band gap switches, and polygon iron core, were shown to deliver power efficiently to the EV battery. An optimized transmitting and receiving coil design, specially tuned for the modified cementitious media, was shown to produce an 86% power transfer efficiency. The properties of the cementitious media are shown to be critical to this holistic power efficiency enhancement. Without the modified media, the power efficiency is reduced to 13% which is dramatically less than the system with 10% iron or 20% magnetite. Improved power efficiency decreases charging time and leads to the robust and reliable EV charging mechanism.

REFERENCES

[1] Jaegue Shin, et al. "Design and implementation of shaped magnetic-resonance-based wireless power transfer system for roadway-powered moving electric vehicles." *IEEE Trans. on Industrial. Electronics*, V.61 No. 3, 2014, pp. 1179-1192.

[2] Takehiro Imura, Hiroyuki Okabe, and Yoichi Hori. "Basic experimental study on helical antennas of wireless power transfer for electric vehicles by using magnetic resonant couplings." *2009 IEEE Vehicle Power and Propulsion Conference*. IEEE, 2009.

[3] S. Verghese, M. P. Kesler, Hall, K. L., Lou, H. T., & Fiorello, R. (2013). *U.S. Patent Application*, No. 13/612,494.

[4] Shu Yuen Ron Hui, Wenxing Zhong, and Chi Kwan Lee. "A critical review of recent progress in mid-range wireless power transfer." *IEEE Transactions on Power Electronics* V. 29 No. 9, 2014, pp. 4500-4511.

[5] Kasra Barkeshli, *Advanced electromagnetics and scattering theory*. Ed. Sina Khorasani. Springer, 2015.

[6] Snyder, K., Feng, X., Keen, B., Mason, T. Estimating. "The electrical conductivity of cement paste pore solutions from OH^-, K^+, and Na^+ concentrations." *Cem. Conc. Res.*, V. 33, 2003, pp. 793-798.

[7] Rajabipour, F., Weiss, J. Electrical Conductivity of drying cement paste. *Materials and Structures*, V. 40, 2007, pp. 1143-1160.

[8] Bu, Y., Weiss, J. "The influence of alkali content on the electrical resistivity and transport properties of cementitious materials." *Cement and Concrete Properties*, V. 51, 2014, pp. 49-58.

[9] ASTM C109 / C109M-16a, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens), *ASTM International*, *West Conshohocken*, PA, 2016.

[10] ASTM C807-13, Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle, *ASTM International*, *West Conshohocken*, PA, 2013.