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Abstract

Inductive Power Transfer (IPT) Charging for Electric Vehicles –a critical look

As we progress into the future of Electric Vehicles, we see improvements in many aspects of this vehicle technology as well as improving consumer acceptance. Many consumers now see Electric Vehicles as a viable improvement for improving gas mileage, reduce emissions, decrease dependence on oil, reduce noise, but also send a statement that energy efficiency is not optional but mandatory as we go forward.

Today's Electric Vehicles have made a tremendous start for this ever increasing market but still many issues need to be resolved. These would include infrastructure changes to accommodate battery charging, communications to ensure proper vehicle identification, equipment robustness, safety, and also convenience. Though many issues can not be understated in their difficulties, convenience can not be understated in like manner since no technology is likely to succeed if the consumer can not easily use it. Remember the first computers without software. Consumers have come to expect convenience as not so much as a requirement any more but more as a given. For this reason, Inductive Power Transfer should be investigated along with other technologies to ensure the success and viability of the EV technology.

Within the Electric Vehicle market, Inductive Power Transfer has the potential to improve substantially consumer convenience. This could involve charging your vehicle while parked at your home or potentially at some parking deck that is equipped with this product. A static charge capability is important since we all drive our vehicles to a location and have set for some period of time but just as important is the potential to improve the overall "Single Charge Mileage" that could exist with a dynamic condition that continuously charges. In other words, a "Single Charge Mileage" is what a consumer would experience as he or she would depart for work in the morning and have the capability of travel a certain distance on one charge. To improve this dynamically would be seamless to the consumer and therefore improve that mileage from that initial charge.

Keywords:IPT,J2954,EMF

1 Introduction

A tremendous amount of work has already gone into this technology and progress continues by many Companies and Universities to show the Promise of IPT, but, is it worth it? This paper will investigate the method of Inductive Power Transfer as a viable emerging technology for the Electric Vehicle Market for use as a static charging station.

Dynamic charging, though hopefully promising, is not the primary focus since there remains considerable work to show viability but will also be discussed. This investigation will detail the science of wireless charging, safety, standards, test methods, comparative approaches, and convenience. Even though convenience is of primary importance for the consumer, the efficiency of the system must also be very high since improved vehicle efficiency does not mean we can subsequently waste energy in other places. Therefore, the efficiencies of each component will need to be analyzed and tested to ensure a minimum level of acceptability. This paper will also research and detail the fundamental areas of the inductive system from plug to battery detailing each component within this series system to determine the overall efficiency.

1.1 What is IPT/WPT or Inductive/Wireless Power Transfer

Essentially based on a simple transformer (fig 1), IPT uses the electromagnetic field to transfer energy between two objects in close proximity at resonance. Input power or charging station sends energy from one source through the inductive coupling to store energy to a receiving source such as a battery (fig.2).

1.1.1 SAE J1773 Magne Charge Paddle

The generation 1 of inductive chargers (fig.3 and 4) included a charge paddle that was placed in the car, such as behind the license plate, to provide the power necessary to charge the battery. This approach was discontinued by GM for the EV1 after the California Air Resources Board selected SAE J1772-2001. This approach utilizes a direct coupling to the car such as a connector that will connect the vehicle to the utility.

The Magne-Charge paddle was approximately 86% efficient at 6.6kW charger using 240Vac / 40A / 60 Hz.

1.1.2 Why Bother with Inductive Charging

It's all about Convenience to the consumer. Years ago when we had gas station attendants (fig 5), this was no problem dealing with the weather. The attendant took care of it. We now want something over our heads to protect us from the elements if we have to get out of the vehicle to do the same chore (fig.6).

The same difference exists between a direct connection for J1772 (fig.7) and for J2954 IPT (fig 8). Convenience and comfort will be very important.

1.1.3 Charging Efficiency between Methods.

Battery characteristics between various platforms range from the Chevy Volt with a 16kWh battery to the Tesla Roadster with a 56 kWh battery. For this paper, I've selected the Magna E-Car with a 33kWh battery for a comparison between charging efficiencies. The calculations will assume a USA average electricity cost per kWh at $0.0983.

J1772: Assumption - 100% efficiency before the battery charger.
Using 3.3kW charger takes 10 hours to charge a 33kWh battery. Using 6.7kW charger takes 4.9 hours to charge. Cost of charging will be approx. ***$3.24***. Basic cost of the unit is around *$900*.

J2954: Assumption - at least 90% eff. before the battery charger. Using 3.3kW charger takes 11hr at min. efficiency for an IPT system. Using 6.7kW charger will take 4.4 hrs. Cost of charging will be approx. ***$3.57***. Basic cost around *$2,000* for a home unit and *$3,000* for outdoors.

As can be seen clearly, the cost of charging is not so painful but the cost of the charging equipment can be somewhat expensive. What will improve the charging efficiency considerably for J1772 direct connection will be the use of DC Charging. This will have the potential of fully charging an EV battery in 25mins. What would help the efficiency of IPT are larger chargers or dynamic charging.

1.2 How does the Charging Process Work

External power from the utility is directed to the primary coil located on the garage floor or pavement and by inductive magnetic transfer the power is received by the secondary coil. This is then converted to usable power to charge the EV's battery (fig.9). A typical electrical and communications flow is provided in fig.10.

1.2.1 Resonant Inductive Theory

At resonance, the inductive reactance (1) equals capacitive reactance (2). This yields an equation for resonant frequency (3) which is essentially the square root reciprocal of the inductance and capacitance.

With the circuit at resonance, then a value known as the quality factor "Q" becomes critical for power transfer (4). This is the ratio of the inductive reactance to the resistance of the coil (5). Therefore, the efficiency of the power transfer depends on the coupling "k" between the inductors and their quality factor Q. As the factor k(Q) increases the energy loss factor decreases (fig.11).

Higher Q values provide greater coupling efficiency and better power transfer though very selective. (See equation 6 for IPT transfer and fig.12 for Q resonant coupling). Since Q is directly proportional to frequency “f” and inversely proportional to the series resistance “R”, the lower the frequency the lower the quality factor is achieved at the same series resistance. In other words, the smaller the Q, the smaller the efficiency of power transfers.

All companies engaged in Inductive Power Transfer use resonant circuits to enhance the effectiveness between the primary and secondary coils. If the primary and secondary coils are at two different frequencies, (i.e. two different suppliers) then you do not have a resonant coupling but an inductive coupling. Efficiency is therefore much lower. (See figure 13 for coupling factor k vs. coil displacement.)

This is the primary reason and importance for interoperability “if” systems are going to be utilized across all platform designs; however, is this really necessary. More on that later.

1.2.2 IPT Approaches

There are basically five approaches (Electrodynamic Induction, Magnetic Resonance Coupling, Resonant Inductive Coupling, Electromagnetic Resonance Coupling, and Microwave Coupling) that are advertised but really only turns out to be just two. It is Magnetic Resonance at a high quality factor or low quality factor or Inductive Coupling. Magnetic resonance is effective over short distances, location is flexible, and it’s unaffected by obstructions but with larger coils and increased complexity. Induction Coupling is well understood, efficient, and relatively inexpensive. But this is less effective over distances and must be aligned.

1.2.3 Systems Efficiency

The efficiency of the entire system from source to load is being benchmarked to greater than 90% to provide a level of power transfer that comes close to a direct connection. This system efficiency then becomes the multiplicative total of sub components within the vehicle. (fig. 14).

1.2.4 Types of IPT Charging

There are four major types of inductive charging. The first is a type A which will be used for residential. The next is type B which will be used for off-road parking similar to parking at meter. The third type is C which is on-road static representative of what would be seen with a bus at the bus stop. The last is type D which is on-road dynamic (fig. 15). All types must have an efficiency of greater than 90%; however, type D will be very difficult to achieve this level. This technology still has a long way to go but improving rapidly but has the potential to decrease driver anxiety greatly.

1.2.5 Competitive Approaches to charging

Research through the internet has shown that there are some significant differences between approaches and some basic similarities (fig.16). Most companies utilize a 3.3kW onboard charger which severely limits the time necessary to effectively, time wise, charge the vehicle. The efficiencies are basically all advertised at >90% with a charging distance of around 20 to 30cm. The big difference is the frequency of the charge transfer from the primary to the secondary coil. This information is difficult to find with some companies providing this information and others preferring not to provide this; however, most it seems are between 20 kHz to 150 kHz with most on the lower side.

1.3 Specifications, Test Scopes, and Safety

The SAE committee J2954 has provided a list of areas that will be addressed within the specification. They are listed in figure 17. Test safety issues are listed in figure 18 and test scope is shown in figure 19.

1.3.1 Interoperability Between system frequency and system differences.

As indicated in prior sections, all companies engaged in Inductive Power Transfer are using their own proprietary designs (fig.20) so the issue of interoperability is very much a focus. This is absolutely necessary for a J1772 direct connect but is it really that necessary for Inductive transfer for vehicles that set either at their place of work or at home where dissimilar systems probably will not happen. There are about seven options for looking at this problem.

The first is “so what”. Is this really needed for short term charging at a shopping centre or is this method going to be used more at home or at work? The second would be accept the inefficiencies that will exist. IPT is not like creating a standard such as a J1772 connector interface or J1773 charge paddle but more like accepting the efficiencies differences like with using a V8 engine. Yes, I understand that this is unpopular but again the primary charging point probably will be at home or at work.

Other options point to specifying the operation frequency, coil design, magnetic field characteristics, field specification for compatibility between primary and secondary coils and lastly specify a WPT coil interoperability test for compliance for coupling of coils. In the authors opinion this is the ideal world but is it really necessary. This will essentially dictate the cost and service but do not necessarily believe that it make for better systems.

1.3.2 EMF Electromagnetic Frequency Safety

Okay, why worry. What this considers is the affects on the human body, what it does, is it safe, and does frequency have anything to do with it (fig.21). The ICNIRP (the International Commission on Non-ionizing Radiation Protection) states for coupling mechanisms between fields and the body; “human and animal bodies significantly perturb the spatial distribution of a low frequency electric field. At low frequencies, the body is a good conductor, and the perturbed field lines external to the body are nearly perpendicular to the body surface.”

Looking at the frequencies that will be utilized which will between 20 kHz and 150 kHz, we see that the frequencies range through the VLF very low frequency and the LF or low frequency. The two important criteria to observe is the Magnetic flux density in Teslas and the Current density measured in Amps/meters squared. The current density is a product of material conductivity and the internal electric field in volts/meter.

The ICNIRP guidelines use for the basic restriction on exposure to EMF is the internal electric field strength E_i as it is the electric field that affects the CNS (central nervous system) and PNS (peripheral nervous system). This value for the basic restriction for E_i is 0.000135 times the frequency which is the basic restriction for human exposure up to 10 MHz (fig.22).

EMF exposure guidelines provided by ICNIRP are given in fig.23 for the electric field as 8.3 kV/m and fig.24 for magnetic flux density as 27uT. Since the magnetic and electric fields are interrelated, the ICNIRP for the electric field can be reduced to the basic limit for the magnetic field. In this way, the properties of inductive transfer can be more easily understood. In fig.25 shows the test setup and results for average body exposure to the magnetic flux density. ARPANSA standard provides that the body average should be no more than 6.25uT and the above mentioned testing showed the body average for IPT to be 4.76uT.

1.4 IPT/WPT Market Activity

Figure 26 provides a look at the various companies that advertise Inductive Power Transfer. This figure also tries to tie these companies with their alliances and joint ventures. For example, Siemens working with BMW, WiTricity ventured with Mitsubishi Motors, Delphi, and Toyota, Qualcomm/Halo with Citroen, WAVE/EDL with ebus, and Evatran/Plugless power with Yazaki and Sears Home Services.

1.5 Finally, what’s this mean

It’s all about convenience to the consumer. The concerns for the direct connection method J1772 is susceptibility to the environment with effects comfort and handling of the equipment. The positive side of this is that the efficiency is nearly 100% not including the battery charger.

The concerns for the Inductive Power Transfer method J2954 are susceptibility to alignment which effects efficiency and also system interoperability. The efficiency has been benchmarked to be greater than 90% and from the research it appears that all companies are comfortable with this.

In the long run, inductive power transfer has some good benefits and probably more when efficiencies improve and dynamic charging becomes more realized; however as we drive forward (the pun is intended), the system(s) that seem to make sense could be a combination of a fast charge J1772 and a dynamic inductive charge J12954. Just a thought!

2 Figures, Tables, and Equations

2.1 Figures

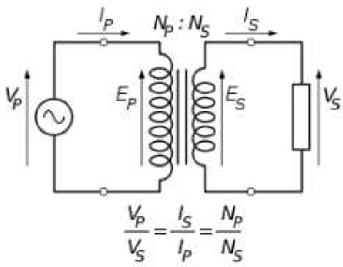

Figure 1: Simple Transformer

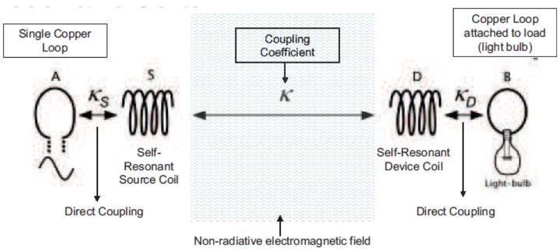

Figure 2: Resonant Inductive Coupling

Figure 3: J1773 Magne Charge Paddle

Figure 4: J1773 Charge station

Figure 5: Gas attendant works the pump

Figure 6: Pump your own gas

Figure 7: In the environment

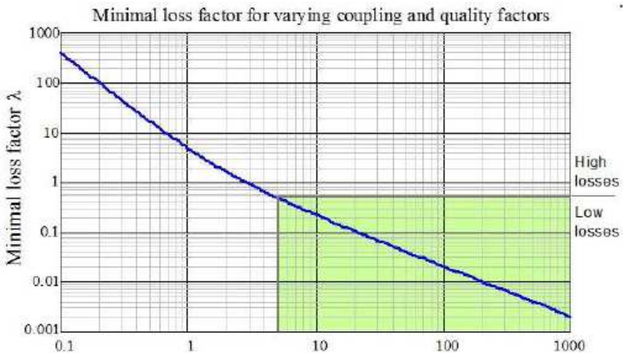

Figure 11: Loss factor to coupling eff.

Figure 8: Inductive Power Transfer

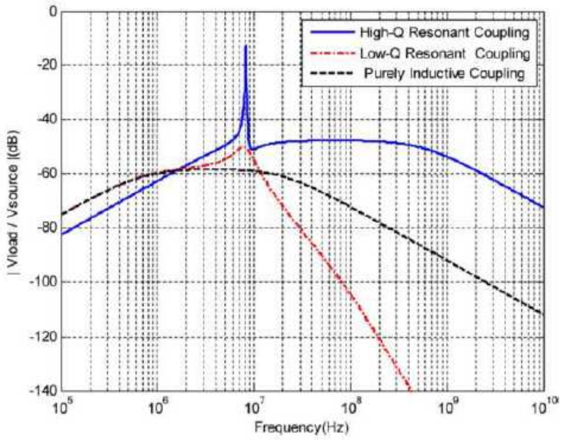

Figure 12: Q levels of resonant coupling

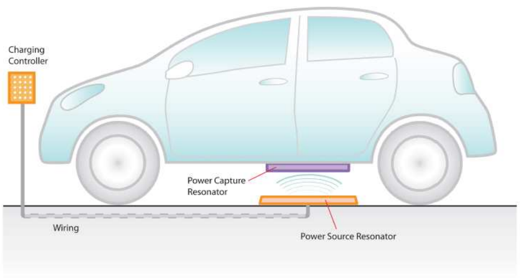

Figure 9: Inductive Process

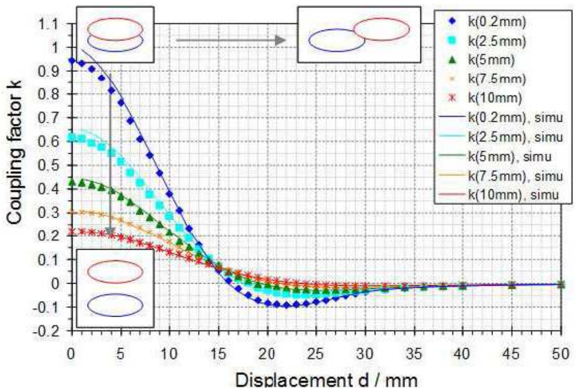

Figure 13: Coupling factor vs. coil movement.

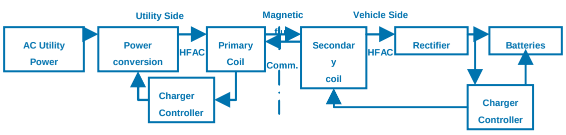

Figure 10: Electrical layout

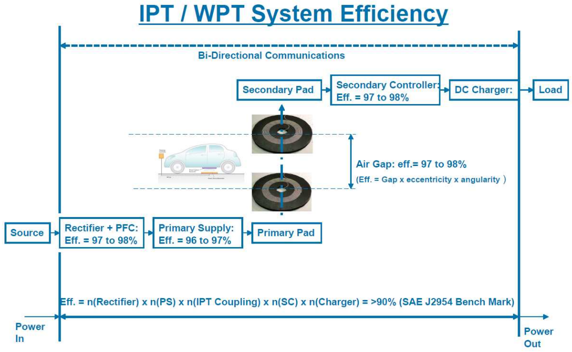

Figure 14: Component system eff.

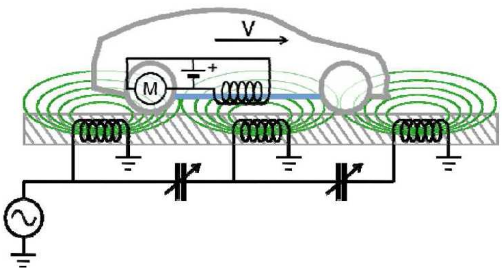

Figure 15: Dynamic transfer

Company Name	Charging power level	Transfer approach	Frequency	Eff.Source to load	Eff. Source to Charger	Type of Charging	Charging Distance	Cost	
Conductix / Wampler	3.68kW	Inductive resonant	20kHz/140 kHz	>90%	--	Static	Larger gaps for trucks and buses	?	
Evatran / Plugless power	3.3kW	Inductive	?	NA	>90%	Static	20 cm	$2400	
WAVE/EDL	5kW	Inductive	?	>85%	>90%	Static and Dynamic	26 cm	?	
WiTricity	3.3kW	Magnetic resonance	?	?	>90%	Static		?	
Halo	3.3kW	Inductive	20-100kHz	>90%	--	Static	30 cm	?	
Siemens	3.6kW	Inductive	?	>90%	--	Static	8-15 cm	?	
Bombarier	??	Inductive	?	??	??	Dynamic	??	?	
Brose -SEW	3.6kW	Inductive Resonant	25-140kHz	>90%	--	Static	??	?	
KAIST	3.3kW	Magnetic Resonant	20kHz	>83%	--	Dynamic	20 cm	?	

20kHz < f < 150kHz (most do not advertise)
Eff. > 90% at charger
Air gaps approx. 25cm

Figure 16: Competitive Approaches

1. Scope/References/Definitions
2. General vehicle and charger system requirements and interface
3. Types of charging
4. System Description
5. Voltage Requirements – AC Supply Voltage & Output Voltage
6. Interoperability – Automatic Tuning
7. Electromagnetic Compatibility (EMI, C)
8. Magnetic Field Definition, Standard
9. Functional/ Physical Requirements
10. Connection Check
11. General Wireless Charging System Requirements.
12. Electric Shock
13. Testing – Dielectric, Environmental, and Mechanical
14. Marking and Identification

Figure 17: SAE J2954 Outline

Issues:

1. *Foreign objects on primary coil*
2. *Magnetic Field or EMF influence on the body*
3. *Charging Battery SOC Levels and rate.*
4. *Temperature Development*
5. *Durability with exposed coils*
6. *Environmental robustness*
7. *Durability of the Electronics.*
8. *Compatibility between systems - detrimental effects*
9. *Minimum performance*

Figure 18: Issues

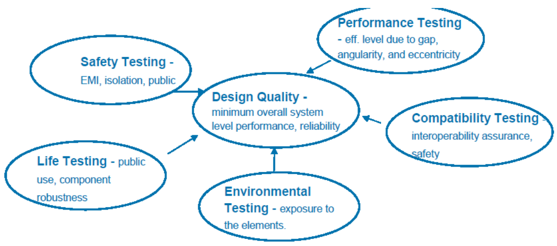

Figure 19: Test Parameters and Scope

Figure 20: Primary and Secondary coils

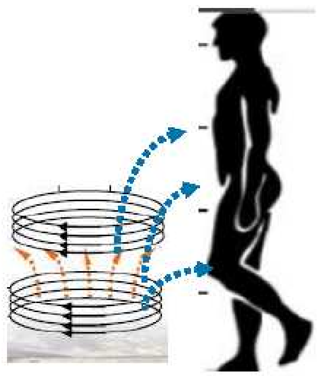

Figure 21: EMF effects on the body

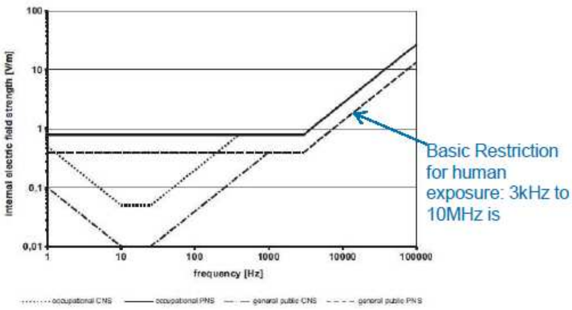

Figure 22: Basic restrictions for Ei exposure at 0.000137(frequency)

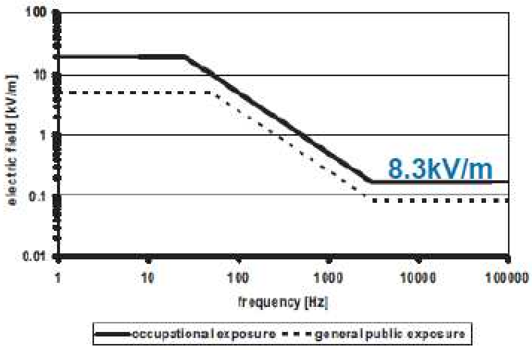

Figure 23: Electric field vs. Frequency

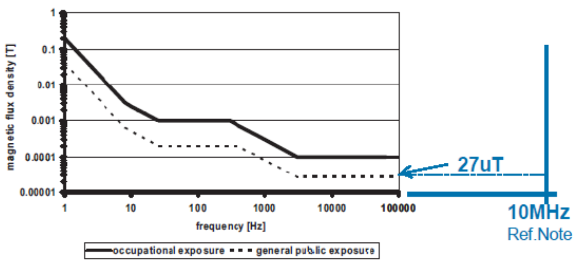

Figure 24: Flux Density vs. frequency

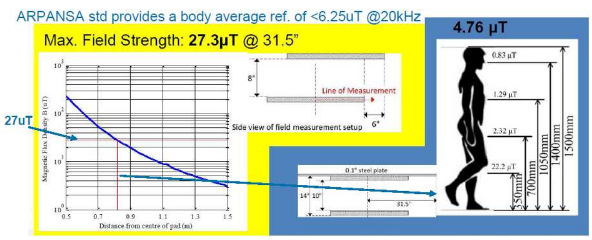

Figure 25: Average exposure on the body

Figure 26: Market Activity (not a complete list)

2.2 Equations

$$f = \frac{1}{2\pi\sqrt{LC}} \quad \text{= Resonant Frequency} \tag{1}$$

$$X_L = 2\pi f L \tag{2}$$

$$X_C = 1/2\pi f L C \tag{3}$$

$$Q = 2\pi f L / R \tag{4}$$

$$Q = X_L / R \tag{5}$$

$$\begin{aligned} P &= Q_2 V_{oc} I_{sc} \\ &= Q_2 \cdot \omega M I_1 \cdot \frac{M}{L_2} I_1 \\ &= \omega {I_1}^2 \frac{M^2}{L_2} Q_2 \end{aligned} \tag{6}$$

Primary Converter — Magnetic Coupling — Secondary Pickup

$$M = k\sqrt{L_1 L_2} \tag{7}$$

3. References

[1] "Guidelines for Limiting Exposure to Time-Varying, Electric, Magnetic, and

Electromagnetic Fields (up to 300 GHz)”; pp.494-522; ICNIRP Guidelines; Health Physics Society 1998.

[2] “Wireless Electrical Transmission”. Web 12 Feb. 2012 retrieved from http://www.wirelesspowerconsortium.com

[3] General and public information regarding Conducix/Wamphler. Retrieved from http://www.conductix.com

[4] ICNIRP (International Commission on Non-ionizing Radiation Protection) Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz – 100 kHz). Published in: Health Physics 99(6):818-836; 2010

[5] Cannon, B.L.; Hoburg, J.F.; Stanci, D.D.; Goldsten, S.C.; “Magnetic Resonant Coupling as a Potential Means for Wireless Power Transfer to Multiple Small Receivers,” Power Electronics IEEE Transactions on, vol.24, no.7, pp.1819-3 1825, July 2009.

[6] Eberhard Waffenschmidt, Philips Research

[7] M.Budhia, G.Covic and J. Boys, “Design and Optimization of Circular Magnetic Structures for Lumped Inductive Power Transfer Systems,” IEEE Transactions on Power Electronics, vol.PP, no.99, pp.1-1, 2011.

[8] General and public information regarding WiTricity. Retrieved from http://www.witricity.com

[9] General and public information regarding Evatran/Plugless Power Retrived from http://www.pluglesspower.com

[10] Schneider, J.; Taskforce Chair; “Wireless Charging of Electric and Plug-in Hybrid Vehicles” SAE International J2954

[11] “Wireless Energy and Power Conversion”; Utah State University Research Foundation. Retrieved from http://www.energydynamicslab.com/business-areas/electric-transportation

[12] Electric Vehicle Charging Systems; www.delphi.com/manufacturers/auto/hevevproducts/charging-cordsets/wrls-chrg/

[13] “Wireless EV Charging Explained”. Retrieved from http://www.autoevolution.com/news/wireless-ev-charging-explained

[14] Suh, In-Soo; “Introduction of On-Line Electric Vehicle System and Pilot Application In the Seoul Grand Park”; March 2011; KAIST OLEV

[15] Boekestyn, A.; Gray, T.; Pedder, S.; “Induction Charging for EV’s; Supplier Business, Ltd, 2010

[16] Chowdhurry, R.; Duong, A.; Hsuch, H,; Tsoi, C.; "Wireless Power Transmission"

[17] General and Public information regarding Bombardier. Retrieved from http://www.bombardier.com

[18] General and Public information regarding SEW Eurodrive. Retrieved from http://www.seweurodrive.com

[19] General and Public information regarding Brose. Retrieved from http://www.brose.com

[20] "EV1 Club Home Page" EV1 Club Retrieved 2007-08-23 "GM Pulls the Plug on Inductive Charging. Letter from General Motors Advanced Technology Vehicles (Letter date 2002-03-15

[21] “Delphi Wireless Charging Systems”; Web 6 Feb. 2011; Retrieved from http://delphi.com/manufacturers/auto/hevevproducts/charging-cordsets/

[22] Zax, D.; “Wireless Charging is Cool but Totally Unnecessary”. Web 7 Feb. 2012; Retrieved from http://www.fastcoexist.com/1677891/wireless-charging-for-electric-vehicles-is-cool-but-totally-unnecessary/

[23] Murray, S.; “Wireless Charging of Electric Vehicles: The Next Big Thing”?; Web 7 June 2011; Retrieved from http://www.ttinc.com/object/me-slovick-20110511.html

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