Wireless Power Transfer: A Survey of EV Battery Charging Technologies

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***Abstract*—In this paper, a comprehensive review of existing technological solutions for wireless power transfer used in electric vehicle battery chargers is given. The concept of each solution is thoroughly reviewed and the feasibility is evaluated considering the present limitations in power electronics technology, cost and consumer acceptance. In addition, the challenges and advantages of each technology are discussed. Finally a thorough comparison is made and a proposed mixed conductive/wireless charging system solution is suggested to solve the inherent existing problems.**

I. INTRODUCTION

Recent attention to transportation electrification and the rise in electric vehicle deployment have led researchers to investigate several aspects of electric vehicle and charging technologies including advanced battery technologies, electric drives, on-board charging systems, and off-board level 3/ fast-charge systems. On-board chargers are burdened by the need for a cable and plug charger, galvanic isolation of the on-board electronics, the size and weight of the charger, and safety and issues with operating in rain and snow. Wireless power transfer (WPT) is an approach that provides a means to address these problems and offers the consumers a seamless and convenient alternative to charging conductively. In addition, it provides an inherent electrical isolation and reduces on-board charging cost, weight and volume.

Recent active program announcements made by Tier 1 automotive suppliers including Delphi, Magna, Maxwell and Panasonic; government organizations and RD centers such as Phillips Research Europe, ORNL (Oak Ridge National Lab), ANL (Argonne National Laboratory), EDL (Energy Dynamics Laboratory), INL (Idaho National Lab), US DOE, US DOT; universities such as University of Tennessee, University of Wisconsin-Madison, University of British Columbia, Korea Advanced Institute of Science and Technology (KAIST), Utah State University; as well as Auto OEMs such as Nissan, GM, Audi, BMW, Chrysler, Daimler, Ford, Mitsubishi, Honda and Toyota on WPT chargers are truly showing the significance of WPT chargers in acceptance and emergence of electric vehicles. Present day active WPT suppliers include: WiTricity, Evatran, Conductix-Wampfler, LG, HaloIPT (Qualcomm) and Momentum Dynamics. In total, there is a wide array of research activities on various WPT concepts. Accordingly, there is a need to categorizing these technologies, in greater breadth and detail than provided in [1].

A typical closed-loop WPT charging system is illustrated in Fig. 1 [2, 3]. The basic principle behind inductive charging is that the two halves of the inductive coupling interface consist of the primary and secondary of a two-part transformer. The charger converts AC utility power to high frequency AC (HFAC) power in the power conversion stage. The secondary side wirelessly receives HFAC from the charger. The received HFAC is converted into DC by a rectifier, which supplies the battery pack.

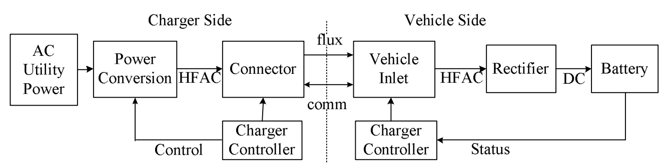

Figure 1. Typical closed-loop WPT charging systems [2,3].

In the following sections, the present state of the art technologies in wireless power transfer are reviewed, compared, and the challenges facing the power conversion systems of the charger are noted.

II. INDUCTIVE WIRELESS POWER TRANSFER

Inductive power transfer (IPT) has been used successfully in several EV systems [2], such as the GM EV1. The charging paddle (the primary coil) of the Magne Charge inductively coupled charger was sealed in epoxy as was the secondary. The paddle inserted into the center of the secondary coil permitted charging of the EV1 without any contacts or connectors at either 6.6 kW or at 50 kW. As it

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depicts in Fig. 2 and Fig. 3, this system is connector-less, but not wireless.

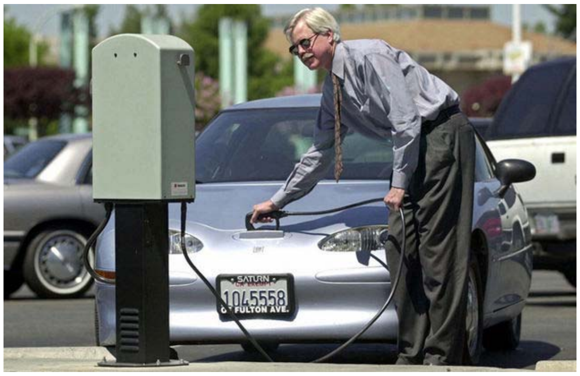

Figure 2. A user plugs the charging cable into an electric powered General Motors EV1.

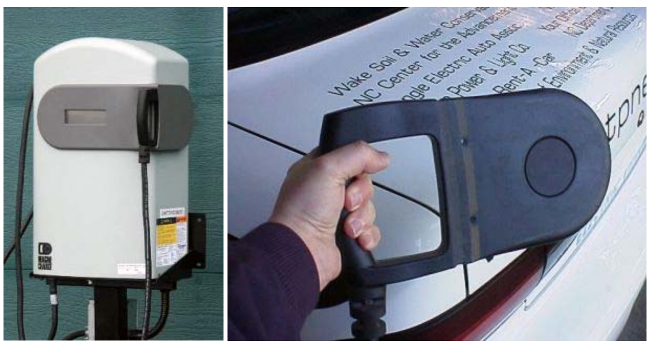

Figure 3. Small paddle inductive station (Left), and the paddle (Right).

The equivalent circuit parameters at the charge coupling interface for an IPT charger are shown in Fig. 4.

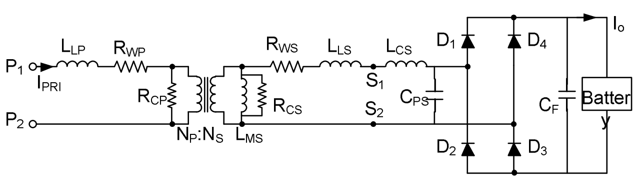

Figure 4. Inductive interface (paddle) equivalebt circuit.

A universal IPT system using 10 kVA coaxial winding transformer (CWT) for a 6.6 kW, 77 kHz, 200/400V EV charger is presented in [4]. One of the most significant benefits of utilizing a CWT is the ability to relocate all transformer core material off-board, thereby minimizing the sensitivity of on-board EV components to flux density and frequency. Utilization of the CWT makes it feasible to implement a single loop, which can operate over wide frequency ranges and being able to be scaled up to meet wide variety of power requirements. An ultra-compact 100 W to 120 kW IPT EV charging system detailing the tradeoffs in designing the transformer for the IPT system is presented in [5]. Core design specific issues primarily concern the impact of nonlinear flux distribution, which results in geometric effects (denser flux around inside corners), eddy current losses and electromagnetic interference. The aforementioned losses are greatly influenced by the core size, increasing when the transformer is scaled up. Symmetrically dividing the secondary winding and assembling the core in a piecewise manner using ferrite materials are reported as possible solutions [5].

III. CAPACITIVE WIRELESS POWER TRANSFER

Capacitive power transfer (CPT) technology has been proposed recently as an alternate contactless power transfer solution [6-9]. As illustrated in Fig. 5, the WPT interface is constructed around a pair of coupling capacitors. The remainder of the power conversion system, including the inverter and rectifier structures remain the same.

Since magnetics do not scale down as desired with decreasing power, at some power level, the cost and size of the galvanic isolation components can be minimized with a capacitive interface. Therefore, the most significant advantage of CPT is its cost and size at lower power levels. However, in high power applications, it is not a preferred solution. For this reason most existing CPT solutions are focused on low power applications and portable electronic devices, such as wireless tooth brush chargers, or wireless cellular phone chargers where the power transfer interface is implemented with capacitive coupled matrix pads.

The application of printing and MEMS technology [10] in CPT shows promise for advancement and acceptance of these technologies in consumer electronics applications.

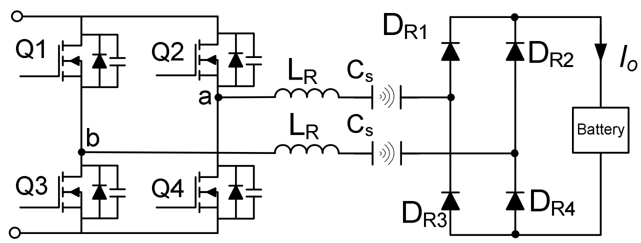

Figure 5. Typical schematic of a series resonant converter circuit constructed around the coupling capacitor [6-9].

IV. LOW FREQUENCY PERMANENT MAGNET COUPLING POWER TRANSFER

Developed at the University of British Columbia, low frequency permanent magnet coupling power transfer (PMPT) combines known elements of magnetic gears and synchronous permanent magnet (SPM) electric machine technology [11, 12]. There are two main physical components, a transmitter and a receiver, as shown in Fig. 6.

A. Transmitter:

A rotating cylindrical, permanently magnetized rotor is driven either by an external, self-contained motor or more directly, by means of static windings that are positioned around the circumference of the rotor itself, separated by an air gap and located either outside of the rotor or inside, if the rotor is hollow .

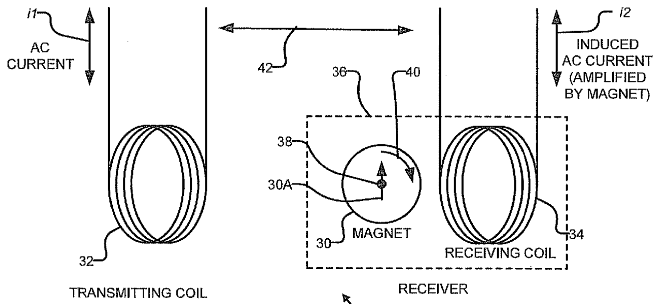

Figure 6. The use of a rotating magnet to enhance inductive power transfer between two coils [11, 12].

B. Receiver:

A similar rotor on the vehicle is positioned within 150 mm and parallel to the utility-side installation during charging. Due to the coupling of the magnetic fields of the two rotors, the vehicle rotor will tend to rotate at the same speed as the utility-side rotor. This is the well-known "magnetic gear" effect.

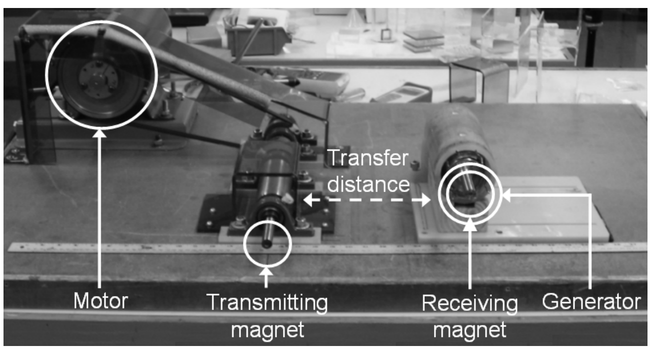

Figure 7. Photograph of the kW scale low frequency permanent magnet coupling power transfer prototype [11, 12].

Energy transfer mechanism: The prototype system uses an externally-driven rotor for the transmitter, as shown in Fig. 7. The proposal for a production transmitter is to have a directly driven rotor, using externally-mounted air-cored windings. The prototype system efficiency is quoted as 81% [11], which is the product of 90% (+/-2%) efficiency for the transmitter and receiver stages. It is believed that the current prototype system has significant opportunities for improvement in terms of both component optimization and system architecture. However, due to the mechanical components used in the transmitter and receiver, this technology may have issues with noise, vibration, and harshness (NVH) and lifetime.

V. Resonant Indcutive Power Transfer

Resonant inductive power transfer (RIPT) is the most popular current WPT technology [13, 14]. It was pioneered by Nikola Tesla and has recently become popular again, enabled by modern electronic components. This technique uses two or more tuned resonant tanks which resonate at the same frequency [15].

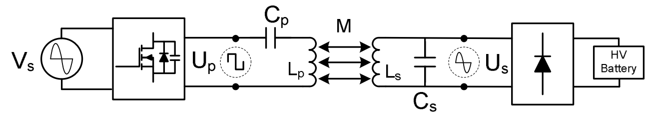

Figure 8. Simplified typical schematic of a resonant inductive charger.

A typical schematic of a resonant inductive power transfer system is illustrated in Fig. 8. The receiver and transmitter contain resonant capacitors, C_p and C_s. Various resonant compensation topologies are proposed in [16]. As noted in [15] the primary functions of the resonant circuits include:

- Maximizing the transferred power,
- Optimizing the transmission efficiency,
- Controlling the transmitted power by frequency variation,
- Creating a certain source characteristic (current or voltage source),
- Compensating variation of the magnetic coupling,
- Compensating the magnetizing current in the transmitter coil to reduce generator losses,
- Matching the transmitter coil impedance to the generator,
- Suppressing higher harmonics from the generator

Efficient resonant magnetic power coupling can be achieved at distances up to approximately 40cm. RIPT systems have several advantages over IPT including increased range, reduced EMI, higher frequency operation, resonant switching of the inverter and receiver rectification circuitry and higher efficiency. However, the main advantage of this concept is that the operating frequency is in kHz range, which can be supported by the current state of the art power electronics technologies.

A RIPT lab prototype was built and tested in [17]. A maximum power transferred of 4.2 kW was reported at 92% efficiency. This unit did not have a front end AC-DC PFC circuit. When multiplied by PFC and power supply efficiencies, the overall efficiency will approximately 85%.

VI. Roadway/On-Line Power Transfer

The application of resonant inductive power transfer (RIPT) technology in public transit systems has been proposed in the literature [18-28]. An on-line wireless power transfer system (OLPT) is illustrated in Fig. 9. The concept is similar to RIPT, however a lower resonant frequency is used and the technology has been reported for application higher power. Technologically, the primary coil is spread out over an area on the roadway and the power transfer happens at multiple locations within this area. Typically, the combination of the input side of the resonant converter along with the distributed primary windings is called the track and the secondary is called as the pickup coil. The system is supplied by a three phase AC system, or high voltage DC system. Considering both the short range of EVs and the associated cost of infrastructure, the feasibility of these charging systems might be unfavorable. However, one benefit is that due to frequent and convenient charging, vehicles can be built with a minimal battery capacity (about 20% compared to that of the conventional battery-powered electric vehicles), which can consequently minimize the weight and the price of the vehicle [26].

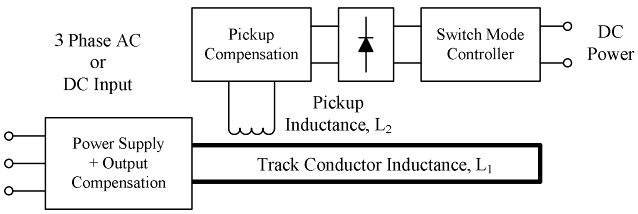

Figure 9. A typical on-line wireless power transfer system [18-28].

A charger with narrow rail width, 10 cm, and large air-gap, up to 20 cm, was proposed in [24]. An efficiency of 74 % was reported at 27 kW output for a 3phase supply input of 440 V, and 20 kHz switching frequency.

VII. Resonant Antennae Power Transfer

Again, pioneered and patented by Nikola Tesla, resonant antennae power transfer (RAPT) has recently been re-invented by MIT and Intel. RAPT uses two or more resonant antennae tuned to the same frequency. The resonant capacitances and inductances are integrated into the antennae. These systems often have large WPT coils (antennae) often helical with controlled separation between the turns to obtain a distributed, integrated, resonant capacitance. Acceptably efficient power transfer is possible at distances up to approximately 10 m [29-32].

An equivalent circuit diagram for a series-parallel resonant wireless transfer system is illustrated in Fig. 10. The concept is similar to RIPT, but the impedance match frequencies are in the MHz range. Ignoring EMI/EMC concerns, basic limits on human exposure to radio frequency radiation are exceeded by most of these systems and difficult to shield without hampering performance and range. Also generating a high frequency power signal in the MHz range is a significant power electronics challenge with today's technology.

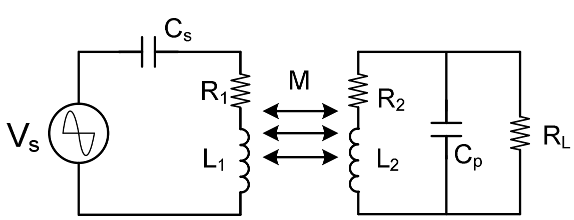

Figure 10. Series-parallel resonant wireless transfer system.

VIII. Commercially Avaliable Systems

Thus far, there are only a handful of wireless charger systems available. These systems are only for pre-commercial trials and none of them have got to the mass production state. WiTricity Corp. is active and has collaborative ties with Delphi Electronics, Mitsubishi Motors Corporation, Audi and Toyota Motor Corporation. Plugless Power (manufactured by Evatran) is another active player in collaboration with Nissan and GM to support Nissan Leaf and Chevy Volt products. Mercedes Daimler and Conductix-Wampfler have elaborated the basics for wireless charging of electric vehicles in a research project. And finally Qualcomm Inc. (acquired HaloIPT) has announced a Wireless Electric Vehicle Charging trial in collaboration with the UK Government, as well as Transport for London.

IX. Challenges

The most significant drawback of all WPT systems is the low efficiency of the energy transferred. Most losses happen during the transfer from coil to coil. In addition, the installation cost of WPT charging systems will be higher than the plug in charging methods due to many factors, including but not limited to increased infrastructure, goods and safety/shielding requirements, and therefore WPT poses to be disadvantageous to EV owners from a cost perspective.

Another significant concern with these technologies are health hazards and basic limits on human exposure to radio frequency (RF) radiation. In Canada, these limits are set by Canadian Safety Code 6 [33]. In the United States, many follow the IEEE C95.1 standard [34], and in Europe users are required to meet the strictest of these standards set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [35]. In Australia the Australian Radiation Protection And Nuclear Safety Agency (ARPANSA) places limits on RF exposure [36].

In addition to RF limits, wireless chargers are required to comply with magnetic field exposure standards primarily recommended by the International Committee on Non-Ionizing Radiation Protection (ICNIRP). ICNIRP establishes regulations on human exposure to time varying electromagnetic fields. ICNIRP standards require that human body should not be exposed to average flux densities greater than 6.25 μT for switching frequencies in the range of 0.8 to 150 kHz. Using the ICNIRP, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) established detailed guidelines on calculating the average flux density. ARPANSA conformance requires that the human body should not be exposed to flux densities greater than 6.1 μT in the frequency range of 10-150 kHz.

X. Comparison and Proposed Solution

A. WPT Comparison

A comparison of the WPT technologies discussed is presented in Table I. IPC is a mature and proven technology. Its only drawback is that it is only a contactless solution, and not a wireless solution. In spite of being around for many years, it did not emerge as a viable answer to the EV market. One reason may be due the low acceptance rate of EVs in the 2000s due to many factors, including the relatively low price of oil.

TABLE I. COMPARISON OF WIRELESS CHARGER TECHNOLOGIES

Technology	Performance			Cost	Size / Volume	Complexity of System	Suggested Power Level
	Efficiency	*EMI*	*frequency*				
Inductive Power Transfer (IPT)	medium	medium	10 - 50 kHz	medium	medium	medium	medium/high
Capacitive Power Transfer (CPT)	low	medium	100 -500 kHz	low	low	medium	low
Permanent Magnet Coupling Power Transfer (PMPT)	low	high	100 - 500 Hz	high	high	high	medium/low
Resonant Inductive Power Transfer (RIPT)	medium	low	1 - 20 MHz	medium	medium	medium	medium/low
On-Line Inductive Power Transfer (OLPT)	medium	medium	10 - 50 kHz	high	high	medium	high
Resonant Antennae Power Transfer (RAPT)	medium	medium	100 - 500 kHz	medium	medium	medium	medium/low

CWP has gained popularity in low power applications because of the poor scaling properties of magnetics at lower power levels. The cost and size of the galvanic isolation components is minimized with a capacitive, rather than inductive interface. Therefore, the most significant advantage of CPT is its cost and size at lower power levels and in high power applications, including EV charging, it is not a preferred charging method.

PMPT technology operates at the supply line frequency, therefore the inherent high frequency problems with other wireless technologies do not exist. However, there are additional concerns with noise, vibration, and harshness (NVH) and life, due to the mechanical components used in the transmitter and receiver, as well as cost and size of this technology.

RIPT and OLPT are likely the most promising technologies among the solutions discussed for EV charging applications. However, the feasibility of these chargers might be unfavorable considering both the short range of EVs and the associated cost of infrastructure.

RAPT is conceptually similar to RIPT but the resonant frequency is in the MHz range, which is up to 100 times as high as RIPT. This can result in problems with human exposure to RF radiation, where limits are easily exceeded by most of these systems. Shielding this radiation is difficult without hampering performance and range. Also generating a high efficiency high frequency power signal in the MHz range is presently a nearly impossible power electronics challenge.

B. Proposed EV Charging Solution

A pure EV needs sufficient battery storage on board to maintain its driving range. Currently, the common lithium ion battery chemistry is estimated to cost around $700/kWh. Consequently, the price of EV's is often nearly twice that of comparable ICE vehicles with the batteries comprising about half the cost [37]. Furthermore, the typical charging time is very long (overnight) and it is very difficult to "refuel" or recharge it quickly like a standard ICE car without compromising battery life. On the other hand, the feasibility of WPT chargers considering both the short range of EVs and the associated cost of infrastructure might be unfavorable, but if the vehicle energy storage and charging system is appropriately designed, a vehicle with a reduced battery capacity (about 20% compared to that of the conventional battery-powered electric vehicles) could be developed. Clearly, this solution would minimize the weight and the price of the vehicle. Therefore, the proposed solution is a combination of fast chargers, on-board chargers and wireless chargers, depending on the vehicle size and its application.

The proposed future integrated wireless/on-board/fast charger solution for small vehicles is illustrated in Fig. 11. Since the battery pack can be smaller, only a 1.6 kW on-board (an integrated conductive/inductive) charger needs to be used to finish the charge cycle. The bulk charging can be done through use of fast off-board DC charging stations. The wireless battery charger can be a stationary small charger installed in a home garage.

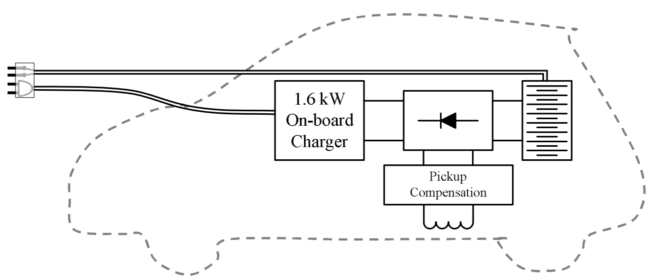

Figure 11. Future viable integrated wireless/on-board/fast charger solution for small vehicles.

The proposed future integrated wireless/fast charger solution for public transit vehicles is illustrated in Fig. 12. The bulk part of charge will be done through fast off-board DC charging stations. There will be no need for on-board charging and the wireless battery charger will be used for finishing the charge cycle while the vehicle is moving. Therefore the wireless battery charger can be an OLPT installed close to bus stops and/or traffic lights.

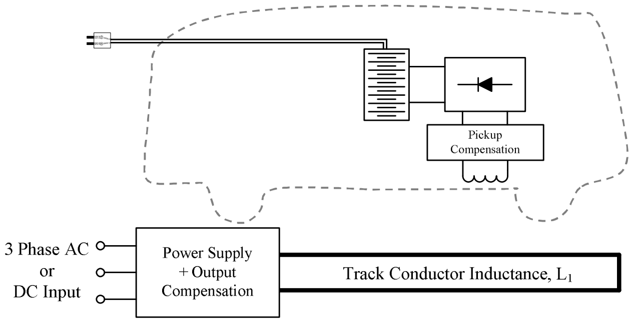

Figure 12. Future viable integrated wireless/fast charger solution for public transit vehicles.

XI. CONCLUSIONS

A review of existing technological solutions for wireless power transfer used in electric vehicle battery chargers is presented. Each solution is discussed in detail and its feasibility is evaluated considering the existing limitation in power electronics technology, cost and consumer acceptance. In addition, the challenges and advantages of each proposed technology is discussed. A thorough comparison and a proposed system level charging solution are suggested to solve the inherent existing problems.

REFERENCES

[1] H.H. Wu; A. Gilchrist; K. Sealy; P. Israelsen; J. Muhs, "A review on inductive charging for electric vehicles " in *IEEE International Electric Machines & Drives Conference (IEMDC)*, 2011, pp. 43 - 147.

[2] SAE J1773, "SAE Electric Vehicle Inductively Coupled Charging," 1999.

[3] SAE J2954, "Wireless Charging of Plug-in Vehicle and Positioning Communication," 2012.

[4] K.W. Klontz; A. Esser; R.R. Bacon; D.M. Divan; D.W. Novotny; R.D. Lorenz, "An electric vehicle charging system with 'universal' inductive interface,," in *IEEE Power Conversion Conference* Yokohama, Japan, 1993, pp. 227-232.

[5] R. Severns; E. Yeow; G. Woody; J. Hall; J. Hayes, "An ultra-compact transformer for a 100 W to 120 kW inductive coupler for electric vehicle battery charging," in *IEEE Applied Power Electronics Conference and Exposition (APEC)*. vol. 1 San Jose, California, 1996, pp. 32-38.

[6] M. Kline; I. Izyumin; B. Boser; S. Sanders, "Capacitive power transfer for contactless charging," in *IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2011, pp. 1398 - 1404

[7] J. Zhu; M. Xu; J. Sun; C. Wang, "Novel Capacitor-Isolated Power Converter," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2010, pp. 1824 - 1829.

[8] C. Liu; A.P. Hu; X. Dai, "A contactless power transfer system with capacitively coupled matrix pad " in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2011, pp. 3488 - 3494

[9] C. Liu; A.P. Hu; N.K.C. Nair; G.A. Covic, "2-D alignment analysis of capacitively coupled contactless power transfer systems," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2010, pp. 652 - 657

[10] T. Sekitani; M. Takamiya; Y. Noguchi; S. Nakano; Y. Kato; K. Hizu; H. Kawaguchi; T. Sakurai; T. Someya, "A large-area flexible wireless power transmission sheet using printed plastic MEMS switches and organic field-effect transistors " in *International Electron Devices Meeting (IEDM)*, 2006, pp. 1 - 4.

[11] W. LI, "HIGH EFFICIENCY WIRELESS POWER TRANSMISSION AT LOW FREQUENCY USING PERMANENT MAGNET COUPLING," in *Engineering Physics*. vol. MASTER OF APPLIED SCIENCE Thesis, Vancouver, B.C., Canada: University of British Columbia, 2007, p. 152.

[12] L. Whitehead, "Systems and methods for dipole enhanced inductive power transfer," Canada: UBC, WO 2010/096917 A1, 2010.

[13] A. Karalis; A. B. Kurs; R. Moffatt; J. D. Joannopoulos; P. H. Fisher; M. Soljacic, "Wireless energy transfer " USA: Massachusetts Institute of Technology, Patent # 7825543, 2008.

[14] A. Kurs; A. Karalis; R. Moffatt; J. D. Joannopoulos; P. Fisher; M. Soljacˇic, "Wireless Power Transfer via Strongly Coupled Magnetic Resonances," *International science journal, American Association for the Advancement of Science (AAAS),* vol. 317, pp. 83-86, 2007.

[15] E. Waffenschmidt, "Inductive Wireless Power Transmission," in *Technical Educational Seminar, IEEE Energy Conversion Congress & Exposition*, 2011, pp. 1-128.

[16] O.H. Stielau; G.A. Covic, "Design of loosely coupled inductive power transfer systems " in *International Conference on Power System Technology, PowerCon 2000*. vol. 1, 2000, pp. 85 - 90.

[17] Matthew Scudiere; John McKeever, "Wireless Power Transfer for Electric Vehicles," SAE International Technical Paper # 2011-01-0354, 2011.

[18] L. Farkas, "High power wireless resonant energy transfer system " USA, Patent # 20080265684, 2007.

[19] L. Farkas, "HIGH POWER WIRELESS RESONANT ENERGY TRANSFER SYSTEM " USA, 2011.

[20] R. A. Pandya; A. A. Pandya, "Wireless charging system for vehicles " USA, Patent # 8030888, 2008.

[21] G. A. Covic; J. T. Boys, "Power demand management in inductive power transfer systems," New Zealand: AUCKLAND UNISERVICES LIMITED, Patent Application # PCT/NZ2010/000181, 2010.

[22] C.Y. Huang; J.T. Boys; G.A. Covic; M. Budhia, "Practical considerations for designing IPT system for EV battery charging " in *IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2009, pp. 402 - 407.

[23] H.H. Wu; J.T. Boys; G.A. Covic, "An AC Processing Pickup for IPT Systems," *IEEE Transactions on Power Electronics,* vol. 25, pp. 1275 - 1284, 2010.

[24] J. Huh; S. Lee; C. Park; G. H. Cho; C. T. Rim, "High performance inductive power transfer system with narrow rail width for On-Line Electric Vehicles," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2010, pp. 647 - 651

[25] S. Lee; J. Huh; C. Park; N.S. Choi; G.H. Cho; C.T. Rim, "On-Line Electric Vehicle using inductive power transfer system," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2010, pp. 1598 - 1601.

[26] S. Ahn; J. Kim, "Magnetic field design for high efficient and low EMF wireless power transfer in on-line electric vehicle " in *Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP)*, 2011, pp. 3979 - 3982.

[27] C.S. Wang; O.H. Stielau; G.A. Covic, "Design considerations for a contactless electric vehicle battery charger," *IEEE Transactions on Industrial Electronics,* vol. 52 pp. 1308 - 1314, 2005.

[28] G.A. Covic; J.T. Boys; M.L.G. Kissin; H.G. Lu, "A Three-Phase Inductive Power Transfer System for Roadway-Powered Vehicles " *IEEE Transactions on Industrial Electronics,* vol. 54 pp. 3370 - 3378, 2007.

[29] T. Imura; H. Okabe; Y. Hori, "Basic experimental study on helical antennas of wireless power transfer for Electric Vehicles by using magnetic resonant couplings," in *IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2009, pp. 936 - 940

[30] T.C. Beh; T. Imura; M. Kato; Y. Hori, "Basic study of improving efficiency of wireless power transfer via magnetic resonance coupling

based on impedance matching," in *IEEE International Symposium on Industrial Electronics (ISIE)*, 2010, pp. 2011 - 2016

[31] S.H. Lee; R.D. Lorenz, "Development and validation of model for 95% efficiency, 220 W wireless power transfer over a 30cm air-gap," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2010, pp. 885 - 892.

[32] S.H. Lee; R.D. Lorenz, "A design methodology for multi-kW, large air-gap, MHz frequency, wireless power transfer systems " in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2011, pp. 3503 - 3510.

[33] "Limits of Human Exposure to Radiofrequency Electromagnetic Energy in the Frequency Range from 3 kHz to 300 GHz," Health Canada, Safety Code 6 (2009).

[34] "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz," IEEE Std C95.1, 1999 Edition.

[35] "ICNIRP GUIDELINES: FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC AND ELECTROMAGNETIC FIELDS (UP TO 300 GHZ)," ICNIRP PUBLICATION – HEALTH PHYSICS 74 (4):494 - 522; 1998.

[36] "RADIATION PROTECTION STANDARD: Maximum Exposure Levels to Radiofrequency Fields — 3 kHz to 300 GHz," AUSTRALIAN RADIATION PROTECTION AND NUCLEAR SAFETY AGENCY (ARPANSA), Radiation Protection Series Publication No. 3.

[37] Aaron Brooker; Matthew Thornton; John Rugh, "Technology Improvement Pathways to Cost-effective Vehicle Electrification," SAE International Technical Paper # 2010-01-0824, 2010.

[38]