International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 10 Issue: 08 | Aug 2023 www.irjet.net p-ISSN: 2395-0072

Three Receiver Coil System for Dynamic Wireless EV Charging

Dynamic Charging of Electric Vehicles by Wireless Power Transfer

Rahul Mittal

Electrical Engineering Department, Arup USA INC, Los Angeles, CA, USA

---***---

Abstract— **A conventional Dynamic Wireless EV Charging system uses a single receiver coil, which often results in increased current, higher losses, and the need for bulkier circuits. This also places a higher demand on the transmitter for consistent flux. This study introduces a design that incorporates three receiver coils in the Wireless Power Transfer (WPT) system, evenly spaced apart. It delves into the necessary modifications at the transmitter end and evaluates the implications on overall costs. The objective is to create a universal design compatible with any Electric Vehicle. The paper contrasts various transmitter coil designs and assesses the advantages of the three-coil system over the traditional single-coil setup. It concludes with a case study on the California freeway, highlighting the potential benefits, market forecasts, and environmental and economic outcomes of the dynamic charging method.**

Keywords—electric vehicles; wireless power transfer; coil design; dynamic charging; coil placement; universal wireless power transfer design; three receiver coils; WPT case study

I. INTRODUCTION

Transportation sector accounts to nearly 28% of the total energy consumed in the United States. US with less than 5% of the world's population is home to one-third of the total automobiles. Personal vehicles consume 60% of the total energy used for transportation. Eighty Six percent of this energy comes from burning of fossil fuels like gasoline or diesel in the cars [1]. Thus, finding alternative fuel sources or promoting the use of electric vehicles is extremely important to bring down this energy consumption and eventually the greenhouse emissions.

In the past few decades, there have been some significant improvements in the battery technology. The battery capacity along with the energy density has drastically improved, so has the rate of charging. But to match the conventional cars, the batteries need to improve further, need to have higher energy density, lesser weight, smaller size, and faster charging capabilities to reduce the charging time, increasing the range in a single charge and reducing the stop time. The short range and high charge times is the most important reason why an EV is not popular for inter-city travel. Having a battery that can charge in the amount of time required to refuel a conventional internal combustion (IC) eengine car, as well as cover a distance comparable to that of conventional car, would make Electric Vehicles (EV's) more desirable and popular amongst the users. Unless, such significant breakthroughs are achieved, alternative solutions need to be considered to promote the use of EV's.

One such notable solution, is a dynamic wireless power transfer (DWPT) system [2], which seamlessly charges an electric vehicle on the go and can reduce or even eliminate the requirement to stop to charge the EV. With its invention back in the late 1800's by Tesla, Wireless Power Transfer (WPT) has seen significant improvements. Moving on from electrical induction to magnetic induction, and successfully using resonance to the benefit in maximum power transfer efficiency through improvements in the coupling factor, the WPT technology is still continuously improving [3], [4]. We have reached the stage where all the energy required by an EV at any given time can be completely provided by WPT. But as this power levels becomes very high, the operating current need to also be is very high, so are the insulation and shielding requirements at both the transmitter and receiver end.

This paper proposes the use of three receiver coils mounted on the car, to extract maximum power from the receiver. The three coils are placed equidistant from each other, the distance between which is determined by considering a pool of cars to make the design universal. The universal model, design considerations and the subsequent transmitter side design changes and benefits are also briefly discussed in the paper along with the impacts and changes to be made on the transmitter side of the WPT system.

The Section II and III explains the Receiver Coil system with impact of charging capability on the coil design and corresponding considerations for single and three coil receiver system. The parameters for design calculations for a three-receiver coil system are explained further in Section III. Construction of Coils. The Transmitter end coil arrangement

Arup

and alignment corresponding to three receiver coil system is explained in Section IV. The Various Transmitter coil cluster configurations along with their flux intensity profile and lane width adjustment is described in Section V. An overall system comparison of single coil with respect to the three coils for various parameters is explained in Section VI followed by a Case study explaining the overall system arrangement, layout and its overall impacts.

II. RECEIVER COIL DESIGN CONSIDERATIONS

To make the complete system universal and accommodate the needs of all the EV's, the three factors to be considered are

- Power received from the Receiver Coil must be enough to meet the discharge rate of the car given the distance to be travelled.
- The charging capability of the battery of each car being different, needs to be taken into account.
- A universal design should have the ability to be retrofitted on to any existing EV, thus the ground clearance, length and width of each car should be taken into account.

One of the major deciding factors, is the battery charging capability of the existing EV's. Charging rate of batteries should not exceed the level 2 charging capabilities, which is in the range of 6.6 kW to 22 kW of continuous power [5]. The actual discharge rate of a typical EV is in the range of 15 kW of continuous power. For the system to become self-sufficient and capable to cover any given distance it is important to provide the power to the EV at a rate greater than or equal to the discharge rate at all times.

A. *Single Receiver Coil System*

A single receiver coil system has just one coil mounted on the EV to tap on to the magnetic field created by the receiver coil. A convenient location is selected as per the make of the car, as the on-car location has no impact on the flux tapped from the transmitter. With difference in the make, the ground clearance of the EV changes, thereby changing the flux linkage and coupling co-efficient. Thus the single receiver coil design needs to be designed specifically for every model of the EV.

To make this design a feasible option, the maximum amount of power should be transferred in the shortest possible time. To achieve this without increasing the current to humungous proportions, the only way to do it is by creating a constant flux at the transmitter end. To draw power in the range of 15 – 20 kW of continuous power, a single receiver coil needs to carry high current at rated voltage.

B. *Three Receiver Coil System*

To draw high amount of power in the range of 15 kW to 20 kW from the transmitter coils, the high current in a single receiver coil system is a design challenge. This paper proposes the use of three coils instead of the traditional single receiver coil system.

The proposed system consists of three receiver coils equidistantly placed from each other. The benefit of having a three receiver coil system is that even if the transmitter side flux is not continuous, a continuous power can be drawn using the three receiver coils as will be discussed in the following section.

III. THREE RECEIVER COIL: SYSTEM DESIGN CALCULATIONS

Unlike the single receiver coil system, the placement of coils in the three-receiver coil system is very specific. The location of the coils in the car, play a very crucial role in the amount of power drawn from the WPT transmitter. To make the design universal, a set of already existing EV's was considered, and based on their dimensions the receiver coil placement was finalized. For the proposed system, the transmitter end coil is designed considering the three coil receiver system. Following subsections show the calculations and parameters taken into account while deciding the placement of the receiver coils in EV's.

A. *EV Specifications and Corresponding Receiver Coil Placement Calculations*

"Table I", shows the details of 4 different EV's considered for design of the Dynamic EV Lane charging, important for determining the distance between the receiver coils.

TABLE I. EV SPECIFICATIONS

Para-meters	EV Make and Model			
	Tesla Model S	***Nisan Leaf***	***BMW i3***	***Ford Focus Electric***
Length	497.8 cm	444.5 cm	408.7 cm	439.4 cm
Width	195.5 cm	177.8 cm	177.8 cm	182.8 cm
Battery Capacity	75 kWh	21.3 kWh	19 kWh	23 kWh
Discharge Rate	17.99 kW	15.66 kW	12.90 kW	16.67 kW

[a] Manufacturers Websites

To make a universal design considering the above mentioned four cars which are the most predominant in today's market, the receiver and the transmitter coil system should be designed taking into account the length and width of each EV. Amongst the above mentioned list, BMW-i3 is the shortest car and thus for a universal system design the total length of the three receiver coils when mounted on the car is fixed to be 400 cm.

IV. Transmitter Coil Design Considerations

A. Construction of Coils

A Resonant wireless power transfer system consists of transmitting coil and receiving coil. When the circuit has been tuned to same resonant frequency, the two coils exchange energy in a high efficiency, while the exchange is weak at other frequency In this study Helical Coils are used that are wound in a spiral fashion using Litz cable conductors and a ferrite core. Design of low loss circuits, matching circuits and shielding [6].

B. Placement of Clusters

A bunch of transmitting coils grouped together in different arrangements and alignments form a cluster [7]. The detailed alignment and corresponding flux behavior is discussed in the section Five. These clusters are closely aligned in a systematic manner such that there is continuous and optimum flux linkage corresponding to the three receiver coil design mounted on the Electric Vehicle. Therefore, the EV dimensions is a prime criterion in determining the cluster spacing for continuous flux linkage thereby providing higher charge and increased efficiency as discussed in section five.

Analyzing the Electric Vehicle dimensions mentioned in "Table I", with a center-to-center measurement, the cluster spacing was calculated to be 400cm. This ensured that all the variety of EV's in market will be able to harness maximum power from transmitting coils. The No load losses caused due to a powered coil with no linkages are thereby reduced in cluster configuration, with the reduced number of clusters with the three coil receiver system. The cluster alignment is such that at any point of time at least one of the receiver coil is completely aligned or two coils are partly aligned with clusters.

C. Design of Segments

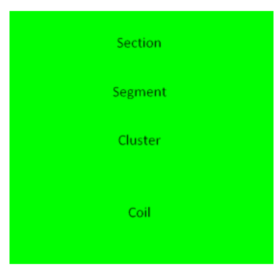
A segment is a group of 30 clusters placed one after another powered by a single High Frequency Resonant Inverter. Each cluster followed by an empty spot occupies 400mm, making the total length of a segment to 1200cm. The total time taken by a vehicle to cover this distance at an average speed of 55 mph is 5 seconds, thus giving a long operating duration of 5 seconds to each inverter. At any given time for one vehicle, the segment on which the vehicle is driving over, is turned ON along with the segment following it. This can be achieved using a GPS and DSRC link [8]. Using such a communication and control protocol, reverse flux linkage can be drastically reduced or even completely eliminated.

Comparing it with a continuous placement of clusters as required for a single receiver coil structure, which requires 60 clusters placed next to each other, the number of transmitting coils running on no-load are almost half at all times. Compared with 58 or 59 coils running at no load, in single coil receiver system (depending upon the location of the receiver), only 28 or 29 coils would be operating at no-load in the three coil receiver system.

D. Design of Sections

A group of segments is referred to as a Section in this paper. The length of a section is fixed at 27.5 miles. With the length of each segment calculated as 1200 cm as above, each section will consist of 3667 segments and 110,010 clusters and 440,040 coils. "Fig. 1" shows the Stacked Venn diagram depicting the relationship between the coil, cluster, segment and section.

Fig. 1: Relationship Venn



V. Transmitter Cluster Design and Configuration

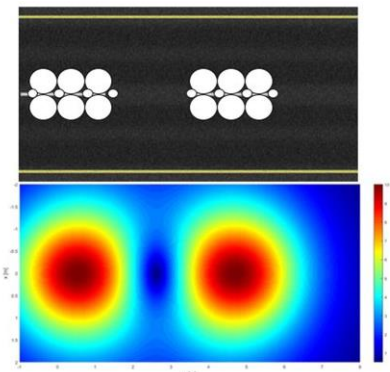
A number of possible transmitter coil structures and configurations were designed and analyzed. A comparative study was performed on these systems and the total impact on cost, and system losses was estimated and taken into account while finalizing the coil design.

A. Six Coil Transmitter Cluster & flux distribution

This configuration consists of 'two sets of three linearly closely placed helical coils, placed adjacent to each other'. Helical Six Coil system described above was simulated in MATLAB to study their flux distribution at a height of 150 mm from the road surface (average ground clearance). "Fig.

2" shows the pictorial representation of the structure mounted on road, depicted in scaled dimensions, along with the flux intensity at the distance of 150 mm for the 2 clusters of six coil system.

Fig. 2: Ten Coil Transmitter & Flux Distribution



"Fig. 3" shows the intensity profile of the flux distribution along the width of the road. If the vehicle drifts towards the extreme ends of the lane, the flux intensity is reduced to half, thereby drastically reducing the power at the receiver end.

B. Ten Coil Transmitter Cluster & flux distribution

This configuration consists of 'two sets of three linearly closely placed large helical coils placed adjacent to each other, with four smaller coils placed between the voids created by the bigger coils'. "Fig. 4" shows the pictorial representation of the structure mounted on road and depicted in scaled dimensions.

Fig. 3: Six Coil System Flux Profile

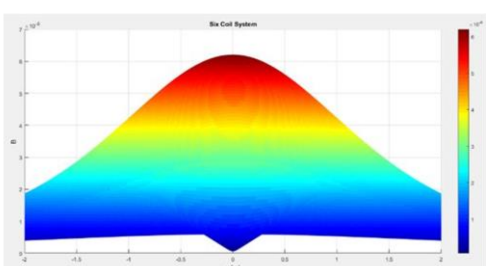
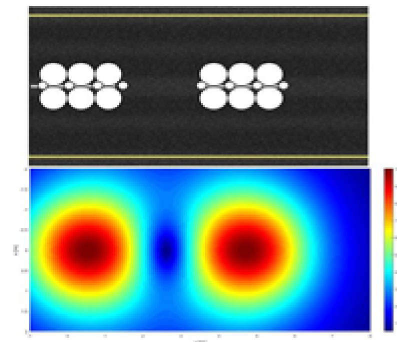
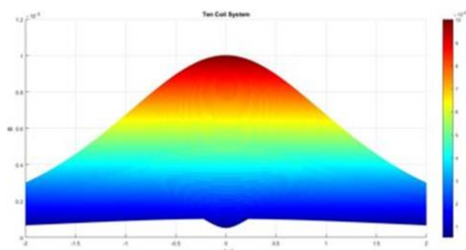


Fig. 4: Ten Coil System Flux Profile



Helical Ten Coil system described above was simulated in MATLAB to study their flux distribution. "Fig. 5" shows the intensity profile of the flux distribution along the width of the road. If the vehicle drifts towards the extreme ends of the lane, the flux intensity is reduced to 75% of its original capacity, thereby not affecting the power at the receiver end by a large margin.

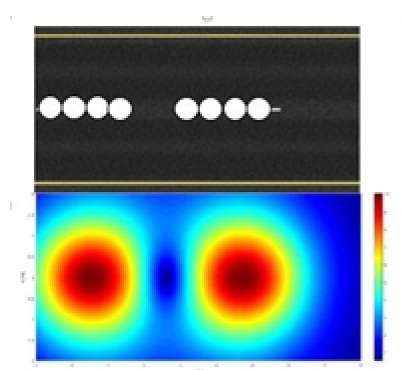
Fig. 5: Six Coil Transmitter Flux Distribution



C. Four Coil Transmitter Cluster & flux distribution

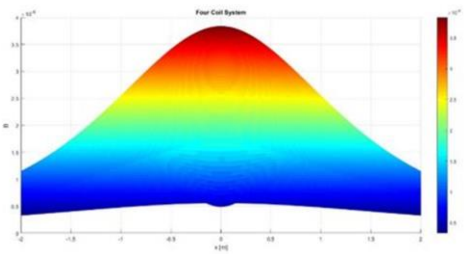
This configuration consists of 'four coils linearly placed at the center of the lane'. "Fig. 6" shows the pictorial representation of the structure mounted on road, depicted in scale. Helical Four Coil system described above was simulated in MATLAB to study their flux.

Fig. 6: Four Coil Transmitter & Flux Distribution



"Fig. 7" shows the intensity profile of the flux distribution along the width of the road. If the vehicle drifts towards the extreme ends of the lane, the flux intensity is reduced to 35% of its original capacity, thereby affecting the power at the receiver end.

Fig. 7: Four Coil System Flux Profile



D. Comparison of different cluster structures

The "Table II", shows a comparative analysis of the three proposed cluster configurations.

TABLE II. CLUSTER CONFIGURATION

Para-meters	**Cluster Configuration**		
	4 Coils	***6 Coils***	***10 Coils***
Current per coil	Lowest	Medium	Highest
I^2R Losses	Highest	Medium	Lowest
Ease of Design	Easy	Typical	Complicated
Flux Intensity Gradient	Steep	Gradual	Flat
Total Cost	Lowest	Medium	Highest

E. Selecting the best system configuration

Auto Aligning of coils on the receiver end side collectively with the 4 coils configuration on the transmitter side will remove the disadvantage of flux linkage problem as stated above in the four coil transmitter design. The set of three receiver coils mounted on the car is designed to dynamically change the location in a lateral axis, depending upon the position of car in the lane. A series of sensors mounted at the front of the car detects the magnetic field and aligns the three receiver coils using a specially designed hydraulic assembly.

VI. COMPARISON BETWEEN THREE COIL AND SINGLE COIL RECEIVER DESIGN

The above discussed parameters are briefly summarized as below:

1) *Flux linkage:* The flux linkage observed in Three Coil receiver system is significantly higher than a single coil system as this provides an overall increase in the surface area in contact with the transmitting coil thereby increasing the linkage.

2) *Continuity of charge:* The continuity in flux linkage as mentioned above will provide a continuous charge to the Battery as compared to a trickle charge as in case of a single receiver coil due to irregular flux linkages. The slope of the flux intensity is constant on the receiver end side.

3) *Ease/Flexibility on Transmission End:* The three receiver coil design reduces the design complexity for transmitting end coils as the clusters can now be placed at a certain distance instead of a continuous arrangement as in [9]. This reduces the copper and corresponding Initial investment involved in embedding the design on road.

4) *Bulky Circuits:* The maximum power transfer capability for a certain coil depends on the conductor thickness and the ferrite core properties. For same amount of power transfer, conductor thickness and corresponding core thickness will be higher for a single coil configuration. The entire power transfer capability gets concentrated on a single coil thus making its design bulkier.

5) *I^2R Losses:* As the amount of current drawn is more for a single coil configuration I2R losses are higher. For a three coil configuration the current drawn by each coil is less thereby reducing the losses and corresponding rise in temperature.

6) *No Load Losses:* As discussed in section four, in three receiver system only half of the coils are running at a time as compared to single coil sytem, results in lower No-Load Losses.

7) *Cost and Reliability:* There is generally a trade-off between coil size, performance, and cost. Coil size and cost are inversely related smaller coils give a better performance, but at a higher cost. This means that a larger single coil geometry costs less than a coil array for a given charging area. Also the reliability of three coil configuration is more than the single coil system as in case of breakdown of the system.

8) Short Circuit Duty: The short circuit current per coil is less for the three receiver coil system as compared to single coil system, because now the current is distributed in a 3 coils configuration and hence the current per coil is reduced.

VII. CASE STUDY

On analyzing on the above mentioned designs for the receiver coil mechanism and the corresponding Transmitting end design a case study is performed to assess the operability and characteristics in a Real Time situation. The EV data described in Section one shows the mileage of different EV's wherein it can be observed that in the present scenario no Electric vehicle is capable of performing Interstate travel or long commutes. The major drawback is the charging station accessibility and corresponding time involved at the charging station as per the level of charge. Implementation of Dynamic Wireless Power charging will allow the user to provide a continuous charge to EV thereby reduction in Battery size and increasing its mileage. Researchers at the Korea Advanced Institute of Science and Technology (KAIST) first tested their On-line Electric Vehicle (OLEV) system in 2009 [9]. Increasing its further application, this will support interstate travel and will also reduce charging down time and eventually addressing the Range Anxiety of an EV user.

A. Los Angeles- Sacremento scenario

The following case study analyzes the 380 mile I-5 freeway stretch between the city centers of Los Angeles and Sacramento, California. The particular roadway behaves as an ideal location for installing and implementing the Dynamic WPT design as it has one of the highest traffic density and works as a major connection between two prime business areas in California. The paper aims at analyzing two scenarios for enabling a Dynamic Wireless Power transfer system between the above mention locations. This system is designed keeping all the market available EV's and their corresponding battery capacity and discharging rates as discussed in Section two.

The First scenario analyzes the segmented design for Lanes. A predetermined length of the lane is powered at a particular instant using the car position and various such segments are layered across the whole distance in a systematic approach. The freeway is divided into zones each having a region of charging wherein the Transmitter coils are embedded in the road and provide the WPT charging to the car, this is followed by a Discharging zone which is the conventional roadway design. The distance between segments is calculated based on the discharge rates of different EV as mentioned in Section II, and calculated lane lengths are shown in "Table III". This study scenario aims at designing a universal lane charging system to ensure that EV's can traverse the desired distance irrespective of the make.

TABLE III. ZONE DETAILS

Para-meters	**Zones**		
	1	***2***	***3***
Charging Zone (Miles)	55	110	82.5
Time for Charging @ 55mph	1	2	1.5
Discharging Zone (Miles)	55	55	27.5
Time for Dis-Charging @ 55mph	1	1	0.5
Total Distance (Miles)	110	165	110
Total Time Required @ 55 mph	2	3	2
Total Travel Time			7 Hours
Total Distance Covered			385 Miles

For different battery capacity and discharge rates as per Section two, lane length calculations are performed for a constant speed of 55mph. Considering an initial battery status of 85% at the start of the trip the following results were obtained. The results ensure a complete trip distance coverage with different residual battery status at the end for further Intra-city travel.

The segmented design aims at optimization of transmitting end section thus reducing the coil complexity, material used, ease of access and corresponding initial investment.

The second Scenario considers a fully powered freeway for the entire stretch of 380 miles. An entire lane termed as EV Lane is designed with transmitter coils embedded in the road that provides charge to the EV via WPT at all times as long as the EV stays on the lane. Combining this with the three coil receiver design a continuous optimum flux linkage is obtained such that the rate of charge is more or equal to rate of discharge based on the make. This ensure complete trip coverage with residual battery for further travel. This design shall promote mass transit using heavy EV's that can be dynamically powered via WPT.

B. Ecological & Environmental Impacts:

As per KAIST, Korea OLEV Design [9] The Dynamic Wireless Lane charging system reduces the Carbon Footprint and overall cost of the transportation system. Implementation of this system on a freeway or highway will increase the EV share in transportation. Assuming an increase in EV users by 30% over the freeway stretch considered in this Case Study it will reduce the CO2 and other emissions caused by (IC) cars considerably. Also the CO2 emissions are further reduced due to the modified design of 3 receiver coil. The reduced battery size and cost incurred compared to IC engine cars over energy consumed as per [9] clearly highlights the advantages of this system and long term economic benefits.

VIII. CONCLUSION

Dynamic Wireless charging is an upcoming field with a huge scope of data collection and field analysis before implementing it on the large scale. .This paper introduces a three coil receiver end configuration with associated modifications and effects compared to existing single receiver coil configuration for charging of EV's dynamically using WPT. Based on simulations and calculations this design method holds valid. In addition, this paper also examines the transmitter side coil modifications, different cluster arrangements like four, six and ten coil configurations and their corresponding flux profiles. A four coil cluster configuration at the transmitter end with an auto alignment feature implemented on the receiver end coils is found to be the optimal solution. Implementing this modified transmitter end design and receiver side combination of Wireless Power transfer system, the output waveform so obtained, when simulated with a combination of rectifiers and six-pulse bridge circuits, resulted in similar waveform as that of a single receiver coil wireless charging circuit. The detail analysis of these wave-forms and the corresponding charging cycles is out of the scope of this paper. Analyzing the charging behavior of different EV's and developing a universal design, a case study is provided to supplement the above design with its calculations and environmental impacts. The author encourage the readers to look into different configurations and aim at universal charging design for Dynamic Wireless charging of Electric vehicles.

ACKNOWLEDGMENT

The author of the paper would like to thank University of Southern California, and Smart Grid Regional Demonstration Project (SGRDP) conducted under American Recovery and Reinvestment Act (ARRA) funded by Los Angeles department of Water & Power (LADWP) and US Department of Energy (USDOE) for their guidance in research towards EV behavior, charging and possible scope of Dynamic Charging.

REFERENCES

[1] Annual Energy Outlook 2014 with Projections to 2040, U.S. Energy Information Administration (EIA) Annual Report, U.S. Department of Energy, April 2014, Available online: http://www.eia.gov/Energyexplained/

[2] In-Soo Suh, Jedok Kim, "Electric Vehicle On-Road Dynamic Charging System with Wireless Power Transfer Technology," in Proc., Electric Machines & Drives Conference (IEMDC), IEEE International, 12-15 May 2013, Chicago, IL.

[3] J. M. Miller and O. C. Onar, "Oak Ridge National Laboratory inmotion wireless power transfer system," in Proc., 1st Conference on Electric Roads and Vehicles (CERV'12), February 2012, Park City, UT.

[4] O. C. Onar, J. M. Miller, S. L. Campbell, C. Coomer, C. P. White, and L. E. Seiber, "A novel wireless power transfer for in-motion EV/PHEV charging," in Proc., IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 3073-3080, March 2013, Long Beach, CA.

[5] J. Kim et al., "Coil design and shielding methods for a magnetic resonant wireless power transfer system," Proc. IEEE, vol. 101, no. 6, pp. 1332–1342, Jun. 2013.

[6] J. M. Miller, P. T. Jones, J. –M. Li, and O. C. Onar, "ORNL experience and challenges facing dynamic wireless power charging of EVs," IEEE Circuits and Systems Magazine, May vol. 15, no. 2, pp. 40-53, May 2015.

[7] N.P. Suh, D.H. Cho, and C.T. Rim, "Design of On-Line Electric Vehicle (OLEV)," Springer, CIRP Design Conference, 21st April , 2010, France.

[8] Musavi, F, Edington, M, "Wireless power transfer: A survey of EV battery charging technologies", Energy Conversion Congress and Exposition (ECCE), 2012 IEEE, pp. 1804 – 1810, Sept. 2012, Raleigh, NC.

[9] O. C. Onar, J. M. Miller, S. L. Campbell, C. Coomer, C. P. White, and L. E. Seiber, "A novel wireless power transfer for in-motion EV/PHEV charging," in Proc., IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 3073-3080, March 2013, Long Beach, CA.