Design and Implementation of Prototype EMIR for Dynamic Charging of Electric Vehicles

Kimberly Mary Crasto, Navan Malhotra, Ramaprasad Poojary

Abstract: Electric Vehicles (EVs) are considered to be one of the most sustainable forms of transportation. Unlike hybrid vehicles or gas-powered cars, EVs run solely on electric power. However, despite their many benefits, EVs are facing major challenges in the market today. The major challenge being its exorbitant costs as compare to fuel-based cars. And, range anxiety also proves to be a hurdle for EVs [6]. Thus, to answer all the aforementioned challenges, we proposed Electro-Magnetic Induction-based Roads (EMIR), a dynamic wireless recharging system. EVs would be able to slip into a special EMIR green lane, recharge their batteries a bit, and slip out. This technology will thus reduce the size of the EV battery, which is the most expensive part of the EV, by increasing its effective mileage and the life of the battery. This paper elaborates on the method of performing dynamic wireless power transfer through resonance based electromagnetic induction. A 163 cm long and a 30 cm wide transmitter coil was designed to transfer electrical energy to an oval-shaped receiver coil with 40 cm as its major axis and 30 cm as its minor axis. The EV battery is dynamically recharged by a charging infrastructure between the road and the vehicle while it is in motion with a high efficiency. The transmitter coils are essentially supposed to be embedded in the road but are placed over the road for visual purposes. The receiver coil is placed under the EV. When the EV goes over the electric road, it gets dynamically recharged. A prototypic EMIR was successfully designed to demonstrate the Dynamic Wireless Power Transfer (DWPT) for EVs.

Keywords: Electric vehicles, Range Anxiety, Dynamic Wireless Power Transfer (DWPT), Electro-Magnetic Induction based Roads (EMIR), Transmitter, Receiver

I. INTRODUCTION

Wireless Power Transfer for Electric Vehicles has been proffered as a technology to charge electric vehicles [1]. Usually, this type of transfer is static i.e. it requires for the EV to be stationary and is up and running. As a result of this, the EV can only be charged while it is halted over a specific spot for a considerable amount of time. However, Dynamic Wireless Power Transfer (DWPT) allows the EV to charge while its moves along the road. The immediate outcomes to this would be a significant decrease in the size of the EV battery and well as the increase in its effective mileage [2].

Kimberly Mary Crasto*, School of Engineering & IT, Manipal Academy of Higher Education, Dubai, UAE

Navan Malhotra, School of Engineering & IT, Manipal Academy of Higher Education, Dubai, UAE

Ramaprasad Poojary, School of Engineering & IT, Manipal Academy of Higher Education, Dubai, UAE

The EV loaded with a smaller battery, will be able to travel longer distances when compared to the same EV sans this technology. Along with these dual benefits, there is additional outcome that would lead to the increased population of the EVs on the road. Due to the smaller battery, the initial costs of the vehicle, which is usually very high, decreases. This is mainly because the battery covers a large amount of the overall costs of the EV. This in turn eliminates the fear of discomfort the drivers feel due to absence of any recharging infrastructure in areas of its unavailability. According to a study, dynamic wireless power recharging is also beneficial to the EV's battery life [3]. Apart from these numerous benefits for DWPT, the major drawback is the infrastructural costs for implementation of this technology [3]. The high initial investment compels us to introduce technical system designs that are economically feasible to implement on a larger scale. This paper takes into consideration the economic aspects of DWPT, which includes the coil designs, drivers and its compensation circuits. In order to construct the proof of concept for DWPT, a suitable design was constructed and implemented. This included an elongated primary coil fitted above the road, for display purposes and an ovular secondary coil fitted below the prototypic EV.

II. METHODOLOGY

The principle of electrical resonance along with electromagnetic induction is employed during dynamic wireless power transfer between the road and the EV. Resonant inductive coupling becomes stronger when both the transmitter and receiver coils resonate. This is required for maximum power transfer at a desired frequency along with its safe transfer without affecting other electromagnetic components.

A. Process Working

The prototype is powered by two polycrystalline solar panels, making it completely self-sustained. Since resonant inductive coupling requires AC, a Zero Voltage Switching (ZVS) module is used, that performs the function of inversion. Two sets of capacitor banks are used as compensation circuits on both, the transmitter and receiver end. Wireless power transfer thus occurs at a distance/air-gap, and the receiver AC must be converted back into a more usable form, DC to power the motors of the EV.

III. DESIGN

The prototypic EMIR is divided into four sections, namely: the power source, inverter, compensation circuits and coils, rectifier and EV battery.

A. Power Source

Two identical polycrystalline solar panels of rated power, 150 W each. The rated voltage and current is 12 V and 10 A respectively. These panels charge two 12 V, 80 Ah solar gel batteries, in series and are regulated by a solar charge controller of a 40 A rating. The following figure 1 depicts the positioning of the charge controller of the left side of the prototype.

Fig. 1. Solar Charge Controller

B. Inverter

A 24 V, 10 A, Zero Voltage Switching (ZVS) module is assigned to each transmitter/primary coil. It converts the incoming DC from the solar gel battery into outgoing AC at a frequency of 12 KHz.

C. Compensation Circuits and Coils

The transmitter and receiver coil have following dimensions:

Table- I: Dimensions of the coils

Type of Coil	Shape	No. of Turns (n)	Length (l) (cm)	Breadth (b) (cm)	Height (h) (cm)
Transmitter	Rectangular	3	163	30	0.6

Type of Coil	Shape	No. of Turns	Major Axis (x) (cm)	Minor Axis (y) (cm)	Average Radius (R) (cm)
Receiver	Oval	6	40	30	35

The radius r, of the Litz wire with silk coating used for the coils is 0.6 cm. The transmitter and receiver coils are separated by an air-gap of 6.5 cm.

The following figures 2 and 3 are the pictorial representations of the transmitter and receiver coils.
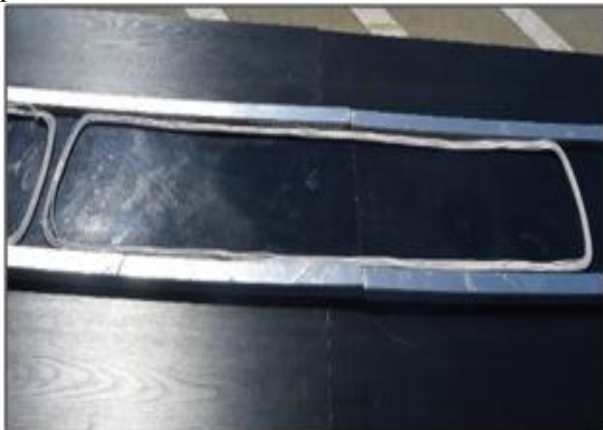

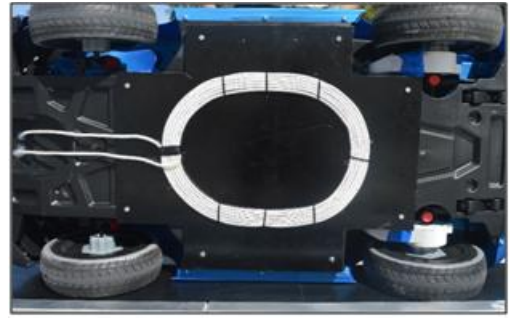**Fig. 2. Transmitter coil laid on a wooden strip of road**

Fig. 3. Receiver coil placed below the prototypic electric vehicle

It can be noticed in the above designs, that the transmitter coil is elongated and rectangular while the receiver coil is oval. This is because the transmitter can cover a larger area with the minimal use of wire. While, the receiver accounts for the deviations that occur due to the misalignment in the position of the electric vehicle [5].

Each transmitter coil has a designated capacitor bank (compensation circuit) [8], that compensates for the difference in the designs and inductances of the primary and secondary coils. These capacitor banks also ensure that the coils resonate at a specific frequency of 12 kHz. The following figures 4 and 5, depict the transmitter side and the receiver side compensation circuits respectively.
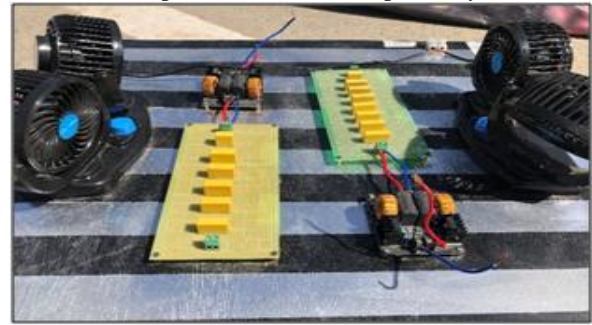

Fig. 4. Transmitter side compensation circuit

Fig. 5. Receiver side compensation circuit

The inductance of the primary coil can be calculated using the following formula:

$$L = \frac{\mu_0}{\pi} \cdot n^2 \left(b \cdot \ln\frac{l}{r} + l \cdot \ln\frac{b}{r} \right) \qquad (1)$$

And, the inductance of the secondary coil can be calculated using the following formula (2):

$$L' = \mu_0 \cdot R \cdot n^2 \left(\ln\frac{8R}{r} - 2 \right) \qquad (2)$$

Practically, the inductances were found to be 27.1 µH and 24.5 µH. The resonant frequency of the coils was calculated by the following formula (3), as explained in [4]:

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad (3)$$

The calculated resonant frequencies for the primary and secondary coils are given in the coil table:

Table- II: Resonant Frequencies of the Coils

Primary Frequency (KHz)	Secondary frequency (KHz)
12.15	12.34

D. Rectifier and Electric Vehicle Battery

After the AC power is dynamically and wirelessly transmitted from the primary to the secondary coil, it must be converted into DC power in order to power the EV battery. Hence, a full bridge rectifier is used with high frequency diodes (UF 4001). Four of these diodes are placed in parallel to form each bridge of the rectifier. This is done to withstand the high current. Along with that, an electrolytic capacitor is also used to act as a filter and thus provide a rectified output to power the motors of the EV.

The following figure 6 depicts the designed bridge rectifier circuit for the secondary side of the system. It is placed in the prototypic electric vehicle.
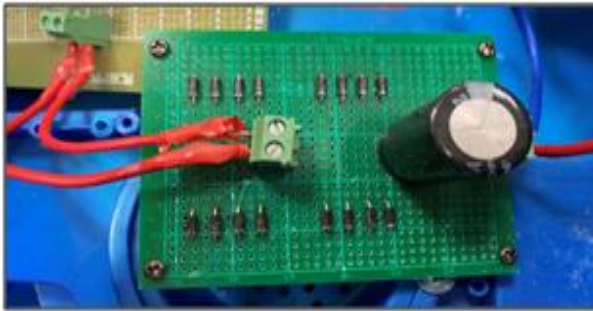

Fig. 6. Bridge rectifier circuit

E. Complete Block Diagram

The output of the rectifier circuit is usually connected to the EV battery. But in this case, due to the limited length of the constructed path of travel, it is directly connected to the electric motors of the EV. This proves that the vehicle is entirely powered by the dynamic wireless power transfer system. The following fig. 7 shows the overall diagram of the project EMIR, from start to finish.
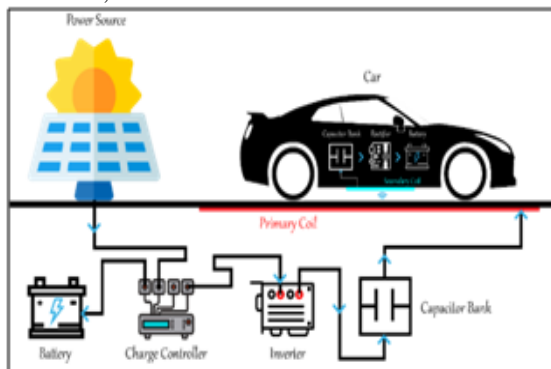

Fig. 7. System block diagram

After the combination of the above-mentioned components, the prototype of Electro-Magnetic Induction based Roads (EMIR) was constructed.

IV. RESULTS & DISCUSSIONS

The system was further tested in three specific locations. This testing was done to obtain the efficiencies of the electrical setup at each of these locations. The overall efficiency was then calculated by averaging the obtained efficiencies. Consider the positions A, B and C of the secondary coil over the primary coil, each given by fig. 8, fig. 9 and fig.10 respectively.
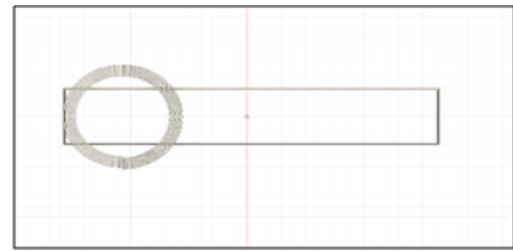

Fig. 8. Position A

Position A, represents the end of the oval secondary coil just over the front of the rectangular primary coil.
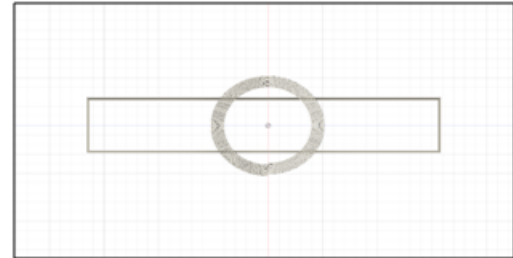

Fig. 9. Position B

Position B, represents the oval secondary coil in the middle of the rectangular primary coil.
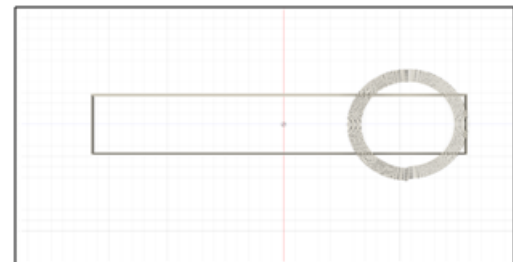

Fig. 10. Position C

Position C, represents the front of the oval secondary coil just over the the end of the rectangular primary coil.

Test Case:

Output of the Rectifier vs. the Input of the ZVS Module

The following table represents data for the primary section.

Table- II: Output values of the primary section

Position	Voltage (V)	Current (A)	Apparent Power (W)
A	24	3	72
B	24	2.75	66
C	24	2.86	68.64

The following table represents data for the secondary section.

Table- III: Output values of the secondary section

Position	Voltage (V)	Current (A)	Apparent Power (W)
A	21	3	63

B	20	2.75	55
C	21	2.74	57.54

Efficiency of the load at any position is given by (4).

$$\frac{\text{Output Apparent Power at the Secondary}}{\text{Output Apparent Power at the Primary}} \times 100 \quad (4)$$

Using the above formula for each of the three positions, A, B and C, we obtain the following efficiencies:

Efficiency of the load at position A $= \frac{63}{72}$ x 100

$$= 87.5 \text{ \%}$$

Efficiency of the load at position B $= \frac{55}{66}$ x 100

$$= 83.33 \text{ \%}$$

Efficiency of the load at position C $= \frac{57.54}{68.64}$ x 100

$$= 83.38 \text{ \%}$$

The following table summarizes the obtained efficiencies.

Table- IV: Efficiencies of the electrical system

At A (%)	At B (%)	At C (%)	Average (%)
87.5	83.33	83.38	84.74

V. THE PROTOTYPE

Fig. 11 and 12 depict the completed prototype. A 9.75 m long, 0.91 m wide and 0.20 m high table was constructed out of wood. The table housed the circuitry as well as the two solar gel batteries.

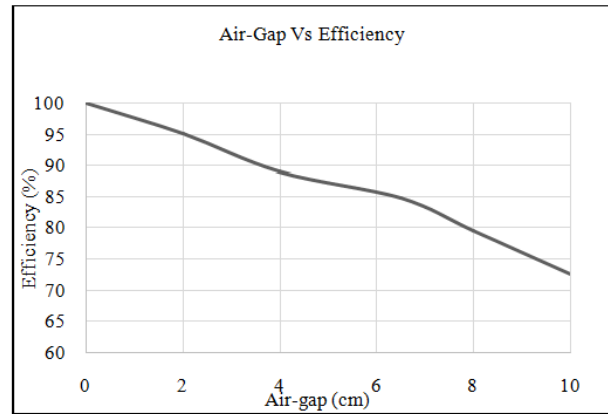**Fig. 11. Front view of Project EMIR**

Fig. 12. Back view of Project EMIR

The primary and the secondary sections were designed to be tuned at the same frequency of 12 kHz and to ensure that the highest coupling coefficient was obtained. The material used for the coils were Litz and USTC, in order to reduce the skin effect and proximity effect that took place at high frequencies. Resonance was achieved due to the usage of the ZVS device, that worked better than an inverter and thus gave a greater efficiency. The compensation circuits consisted of capacitor banks made of metallized polyester (MKP). They were used for high switching applications and hence prevented themselves from getting thermally damaged. The following graph depicts the change in the efficiency when the distance between the primary and the secondary coil is varied [7]:

Graph-I: Air gap vs efficiency

It is thus observable that, as the air gap increases, the efficiency of the dynamic wireless power system decreases.

VI. CONCLUSION

The Project EMIR, was constructed to achieve three major goals namely:

i. The proof of concept
ii. High efficiency
iii. Safety

Our team was able to successfully perform in all the areas. We achieved the proof of concept by powering our prototypic electric vehicle dynamically and wirelessly over a stretch of a 9.75 m constructed wooden path. A high load efficiency of 84.74 % was obtained, which indicated that the constructed electrical system had a low energy loss. Due to the utilization of the principle of resonance, power was transferred only when the resonant frequency of 12KHz was achieved. This prevented power from being induced in any surrounding conducting objects. It thus ensures that the people in EVs as well as in the surrounding areas are completely safe from the electrical system and thus the magnetic field is well below the allowed 25 mT [9].

Four transmitter coils were placed in the path of travel. They were placed within a specially designed wooden plank with a centre groove that accomodates each coil. This was done to ensure that the EV is well directed and does not deviate from its path since it is autonomous when it receives electric power from the primary coil. The EV is given an initial push after which is travels along the built track, without any human intervention. It then stops, when it reaches the end of the primary coil.

This proves that no electrical power is received by the EV when it is not over the primary coil. When project EMIR is upscaled, it will be possible to physically show the charging of an EV battery i.e. the increase in the percentage of the EV battery level can be easily demonstrated.

ACKNOWLEDGMENT

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AUTHORS PROFILE

Kimberly Crasto is currently an undergraduate student at Manipal Academy of Higher Education in Dubai, UAE. She has consistently been the highest academic performer of her branch. The initial proposal of Electro-Magnetic Induction based Roads (EMIR) won a grant of AED 25,000 under the Expo Live University Grant Program. Project EMIR won the first place in the IEEE competition under the senior design category held at Ras Al Khaimah, UAE in April 2019. This project also won the first place in Future Generation Competition held at the World Trade Center, Dubai in March 2019.

Navan Malhotra is currently an undergraduate student at Manipal Academy of Higher Education in Dubai, UAE. He has a keen interest in electrical software and thus has successfully completed courses on AutoCAD Electrical and PLC/SCADA. The initial proposal of Electro-Magnetic Induction based Roads (EMIR) won a grant of AED 25,000 under the Expo Live University Grant Program. Project EMIR won the first place in the IEEE competition under the senior design category held at Ras Al Khaimah, UAE in April 2019. This project also won the first place in Future Generation Competition held at the World Trade Center, Dubai in March 2019.

Ramaprasad Poojary is working as an Associate Professor at Manipal Academy of Higher Education, in Dubai, UAE. He has about 20 years of teaching & 6 years of research experience. He has pursued his B.E. in Electronics & Communication Engineering and MTech. in Digital Electronics and Communication from NMAMIT, Karnataka, India. He did Ph.D. in the area of Dental Image Registration from VTU, Karnataka, India. He has published many journals in the area of Image Processing. Presently he is mentoring the undergraduate project EMIR. He has worked on several university funded projects. He will be submitting a proposal for ANPR based funded project by Manipal Academy of Higher Education Dubai Campus.