A New IPT Magnetic Coupler for Electric Vehicle Charging Systems

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***Abstract*- Inductive Power Transfer (IPT) is a practical method for recharging Electric Vehicles (EVs) because is it safe, efficient and convenient. Couplers or Power Pads are the power transmitters and receivers used with such contactless charging systems. Due to improvements in power electronic components, the performance and efficiency of an IPT system is largely determined by the coupling or flux linkage between these pads. Conventional couplers are based on circular pad designs and due to their geometry have fundamentally limited magnetic flux above the pad. This results in poor coupling at any realistic spacing between the ground pad and the vehicle pickup mounted on the chassis. Performance, when added to the high tolerance to misalignment required for a practical EV charging system, necessarily results in circular pads that are large, heavy and expensive. A new pad topology termed a flux pipe is proposed in this paper that overcomes difficulties associated with conventional circular pads. Due to the magnetic structure, the topology has a significantly improved flux path making more efficient and compact IPT charging systems possible.**

I. Introduction

Electric vehicles (EV) help reduce dependence on fossil fuels, emission of greenhouse gases and emission of pollutants. Consequently, EV uptake has been increasing since the 1990's but market penetration has been low because EVs are not as cost effective as conventional vehicles due to the large battery required for a comparable range [1]. In order for pure EVs to gain widespread adoption, major improvements are required in battery life, cost and grid connection. The latter allows opportunistic charging after each trip rather than a long charge at the end of the day. As a result, battery wear is significantly reduced by minimising the depth of discharge and the EV has a lower cost since a smaller battery is required [1, 2]. With presently used contact based connection systems, opportunistic charging creates a major inconvenience for EV owners since the vehicle needs to be physically plugged in at the end of every short journey. In addition, charging can be done outdoors where exposed contacts present a safety hazard.

Inductive Power Transfer is based on Ampere's and Faraday's Laws, it uses a varying magnetic field to couple power across an air gap to a load without physical contact. There are inherent advantages since the components are electrically isolated, operation in wet environments presents no safety risks and such conditions do not affect performance. IPT produces no contaminants and is reliable and maintenance free unlike conventional plug or brush and bar contact based methods [3]. IPT is presently used in numerous industrial applications such as materials handling and IC fabrication. The systems vary in capacity from 1W–200kW and can be used to both power and recharge robots, mobile phones [4], Automatic Guided Vehicles, electronic devices [5], recreational people movers [6], buses and EVs [7-9]. Inductive charge paddles have been built as a safer option compared to plugs but the paddle still needs to be manually inserted into the vehicle making long term use inconvenient [10, 11].

IPT systems may be divided into two distinct types: distributed systems that consist of one or more movable loads that may be placed anywhere on a track, and lumped systems that only allow power transfer at a defined location. The inductive couplers in the latter system type are referred to as Power Pads and are the subject of significant ongoing research to find the most practical and commercial solutions. IPT is continually finding new applications where safety, convenience and reliability are required however large scale implementation in EV charging systems has been hitherto limited by performance of the Power Pads. Improved coupling ensures systems are as cost effective and efficient as possible and this is extremely important if IPT is to become a preferred method for recharging EVs.

The purpose of this research is to determine the fundamental limits of existing inductive couplers by comparing flux paths, and to propose and test improved coupler designs. The pads are designed in the context of EVs but are easily scalable and efficient designs result in considerable long term cost and energy savings.

II. IPT Concepts

An IPT system comprises three main components as shown in Fig. 1. The power supply produces a sinusoidal current in the 10-40 kHz frequency range that excites the inductive track pad. The parallel compensation capacitor, C_1, is chosen so that its impedance is matched to that of the track at the operational frequency. This allows track current, I_1, to resonate and the large reactive current creates a greater flux density at a given distance from the track than if only the output of the supply inverter was used to drive the track directly. The pads in this paper are excited with a current of 23A and allowing this current through the switches will result in significant losses. Compensation means the switches only have to provide the real power and losses therefore the typical switch currents are in the order of hundreds of mA when the system is resonating with a track current of 23A but not supplying power. The switch currents are approximately 10 to

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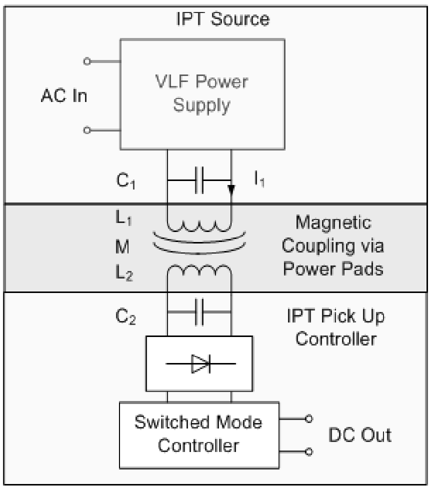


Fig. 1. IPT system components.

15A when the system is supplying a 2kW load. The power output of the investigated system is 2.2-2.4 kW as this is the power typically available from a standard 230V household power socket.

The power coupled is proportional to flux intersected by the Pick Up (PU) coil and compensation minimizes the VA rating of the power supply for a given load [3]. The track and PU pads act as a loosely coupled transformer that enables power transfer over relatively large air gaps. The IPT PU consists of the PU pad inductance L_2, tuning capacitor C_2, a rectifier and a switched mode controller. The pad inductance is tuned for resonance with C_2, this compensates for the relatively large leakage inductance allowing greater power transfer. The voltage across C_2 is rectified and a modified boost converter controller enables the resonant tank to operate at a defined quality factor (Q) to increase power transfer and provide a usable DC output. In the case shown, where parallel tuning is used, the voltage across the resonant tank is controlled by shorting or opening the switch in the boost converter. The power output in the load resistance is V^2/R and this can be increased by increasing the resistance and allowing the resonant voltage to increase.

Where the boost controller differs from a conventional boost converter is the operation of the switch, it is used to decouple the PU from the track. Decoupling is achieved by shorting the pad inductance and is necessary to ensure that the PU coil does not compromise the stability of the system [3]. The power output of an IPT system (P_{out}) is quantified by the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) of the PU pad as well as the quality factor as shown in (1). In a system where the tuning capacitor is in parallel with the pad inductance, Q is the ratio of V_{out} to V_{oc}.

$$P_{out} = P_{su} * Q = V_{oc} * I_{sc} * Q = \omega M I_1 * \frac{M I_1}{L_2} * Q = \omega I_1^2 \frac{M^2}{L_2} Q \qquad (1)$$

Here P_{su} is the uncompensated power, ω is the angular frequency of the track pad current I_1, M is the mutual inductance between the pads and L_2 is the inductance of the PU with the track pad open circuited. As shown in (1), the output power is dependent on the power supply (ωI_1^2), magnetic coupling (M^2/L_2) and PU controller (Q). Increasing the power output and separation is highly desirable but efficiency is limited by the operational frequency (switching loss) and current rating (copper loss) of the system. Allowing a system to operate at a high Q boosts power transfer but in practical applications it is constrained to 4-6 due to component VA ratings and tolerances [3]. Consequently, the greatest increase in system performance can be achieved by proper magnetic design. The coupling factor, κ, shown by (2), provides a useful measure for directly comparing the magnetic properties of different pad topologies. The track and PU pads are typically constructed in the same manner as such have identical inductances and each pad has the same number of turns for convenience. The coupling factor can be easily determined by taking two measurements with an LCR meter. The subscripts 'o' and 's' refer to the opposite pad being either open or short circuited, the primary and secondary pads are numbered *1* and *2* respectively.

$$\kappa = \frac{N_2}{N_1}\frac{M}{\sqrt{L_{1,o}L_{2,o}}} \approx \sqrt{\frac{(L_{1,o}-L_{1,s})}{L_{1,o}}} \qquad (2)$$

The power transferred is proportional to κ^2, which is equal to M^2/L_2 if $L_2=L_1$ and $N_2=N_1$. Improved coupling significantly increases the system efficiency at a given current and frequency. Well designed pads will be even more important as EVs become widely adopted and will save a considerable amount of energy when such charging systems are deployed in mass.

III. Fundamental Flux Distributions

Power Pads need to fulfil several requirements to enable practical application on an EV. The pads should be as thin as possible for ground clearance and fitting, operate with a large air gap (~150-200mm), be lightweight to minimise vehicle energy requirements and have good tolerance to misalignment to allow easier parking. Designs using pot cores [8], U cores [12] or E cores [13] are unsuitable for EVs due to excessive thickness or fragility since large pieces of ferrite are required. These topologies are also necessarily sensitive to horizontal misalignment because the coupling surfaces are relative small compared to the size of the pad. The most common coupler designs use a circular pad [4, 6] and previous work has been done to optimise such a design for a 2kW charging system [14]. The pad allowed the system to couple 2kW across a 200mm air gap and allowed a maximum horizontal offset of 130mm when operated with practical Q's less than 6. However this alignment constraint still makes parking challenging.

It has been noted that regardless of how optimised a design is, the fundamental flux paths in a circular pad remain relatively unchanged. The height of the flux path above the pad determines the coupling between pads and clearly higher paths are favourable. For a circular pad, the fundamental

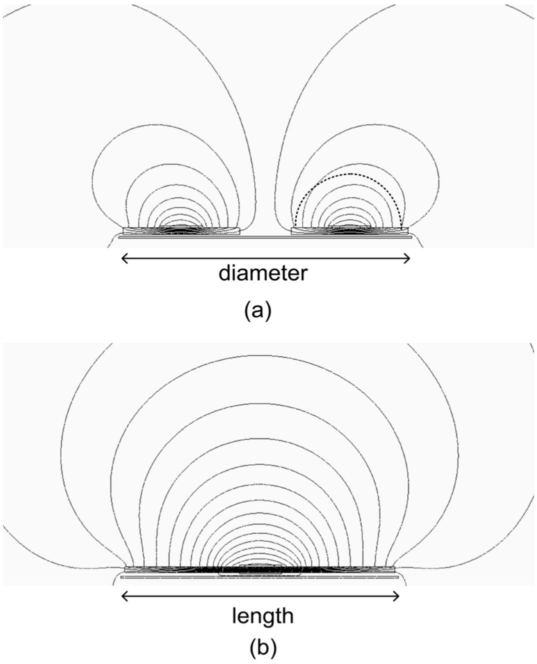


Fig.2. 2D flux plots for (a) circular (b) bar track pads

height of the flux path is roughly proportional to one quarter of the diameter as shown by the dashed line on a cut plane through the centre of a track pad in Fig. 2 (a). The flux density drops significantly at the desired 150-200mm height. The one quarter diameter height relationship results in pads that have to be impractically large to obtain desirable coupling values. For example, a 700mm pad had a κ of approximately 0.17 at 175mm (¼ of the diameter).

Due to the nature of magnetic fields, a preferred flux path is proportional to half of the pad length. This is possible if a shaped bar topology is used, a 2D flux plot for such a pad is shown in Fig. 2 (b) noting the conditions were the same for both simulations (2(a) and 2(b)). Clearly a bar shaped ferrite will offer better coupling since the flux density in the desired operation region is higher compared to that of a circular pad.

IV. Implementation of the Bar Topology

Assuming that the desired coupling factor could be achieved at a height of one half a pad length, a 550mm long test pad was constructed with the aim of achieving a κ of 0.2 with a 200mm air gap. The pads with the aluminium back plate removed from the PU are shown in Fig. 3. Note wings were added to the ends of the pads to further improve tolerance to misalignment with the minimal amount of extra ferrite. Inductance measurements were taken with an LCR meter and κ was calculated from (2) to be 0.07, this value was far lower than expected.

The poor coupling is due to a low reluctance short flux path around the coil, which only covers a small portion of the midsection. As a result there is little flux exiting or entering the pad from the ends resulting in a low flux density 200mm above the pad. This effective short circuit can be mitigated by completely covering the midsection however the high inductance due to the large number of turns would require impractically high voltages to obtain the desired current. Internal compensation capacitors may be used in series with the pad inductance to effectively lower the impedance seen by the power supply, however capacitors compromise the long term reliability of the pad and add significant cost. Excessive compensation makes the power supply unstable; it is typically designed to drive a pad inductance with up to 15% variation. An LCL impedance converting network is used to convert the voltage sourced inverter to a current source that is suitable for driving the pad inductance. The first inductor and capacitor are internal to the power supply and the track forms the last inductor of the network. All three components need to have essentially identical impedances at the operating frequency. Excessive deviation from the desired inductance causes the inverter bridge to source large reactive currents that increase losses and may damage the switches [15]. The track pad inductance typically varies by 10% as the PU pad is brought within the targeted operating range and moved horizontally. The series compensation is fixed as such the relatively small variation in pad inductance becomes a large percentage change in impedance seen by the power supply. This makes the system impractical as it is extremely sensitive to PU movement. Also, the length of wire required to cover the whole midsection would increase copper losses and make the design less cost effective. A compromise is to wind a large pitch coil however it has been experimentally determined that the effective length of the coil decreases if the pitch is greater than a few wire diameters due to flux leakage through the gaps. These small flux loops around spread conductors do not increase coupling and add significantly to the pad inductance reducing the coupling factor. These conflicting requirements have resulted in the development of a flux pipe as described in the next section.

Fig. 3. Bar pads with back plate removed from pick up.

V. Flux Pipe

The flux pipe consists of two coils positioned at ends of the midsection of a pad as shown in Fig. 4 (a). The Tx and Rx are the flux transmitting and receiving surfaces, both track and PU pads are identical. The coils are electrically connected in parallel to lower the impedance and are connected magnetically in series since flux from one coil passes through

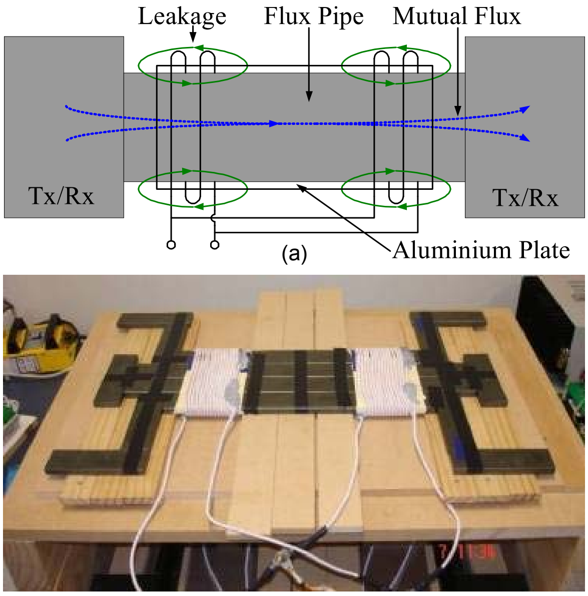


Fig. 4. Flux pipe (a) concept with coils in parallel (b) prototype flux pipe with two 15 turn coils.

to the other. The mutual flux between coils links with the PU to couple power. A small aluminium plate is placed on the upper surface of the pad above the coils to minimise leakage flux. The shielding increases the flux between linkage between coils and hence coupling to the PU. The aluminium backing and shielding plates should be isolated or else they form a shorted turn around the pad, the small gap between the plates results in leakage flux as shown in Fig.4 (a). The quality factor of a pad is its impedance divided by AC resistance at the operating frequency and is the ratio of the energy stored to energy lost in a pad. The quality factor of the pads has been measured and there is no indication that the aluminium will experience excessive heating if it is placed approximately 5mm above the coils.

The inter-coil coupling factor for a single pad is 0.6 and has been optimised via 3D finite element models to create the highest possible flux path above the pad. The inter-coil coupling can be increased by moving the coils closer together however that results in a lower effective pad length. Conversely if they are moved to far apart the mutual flux between coils drops reducing coupling to the PU.

A prototype flux pipe was constructed with standard rectangular ferrites as shown in Fig. 4 (b). The ferrites have been placed in such a manner that there is no continuous gap in the direction of the flux in the midsection. This reduces fringing that would cause loss in the aluminium backing plate. The flux pipe is four bars wide to prevent saturation and each coil comprises 15 turns of 6.36mm^2 Litz wire. Coupling measurements were taken with an LCR meter and from actual I_{sc} measurements when the track pad was excited with 23A at 20kHz. The single phase unity power factor supply described in [15] was used for these measurements. Results from the LCR meter are at most 5.5% higher than those calculated using actual I_{sc} measurements over the complete range of separations of interest (100-200mm) however between 140 – 200mm the results are within 1.5% of each other. The two pads using the flux pipe achieved a coupling factor of ~0.2 at 200mm which is significantly better than the 0.15 obtained using the 700mm circular pad described in [14]. In practice this means the power transferred is almost 1.6 times higher and enables satisfactory operation at 200mm on an EV.

Coupling factors of around 0.2 are preferable for the reliable operation of an IPT power supply. Excessively large coupling factors result in a significant shift in the track inductance that causes the inverter to source large reactive currents as discussed in section IV.

A 3D finite element analysis simulation model of the flux pipe was created based on readily available "I" cores measuring 93mmL by 28mmW by 16mmT. The position and structure of the flux launching wings has been optimised to increase the horizontal tolerance of the pad. The plot in Fig. 5(a) shows the uniformity of the flux density in the flux pipe. In a physical system the peak flux density will be double that shown. The supply does not have a firm DC bus to minimise

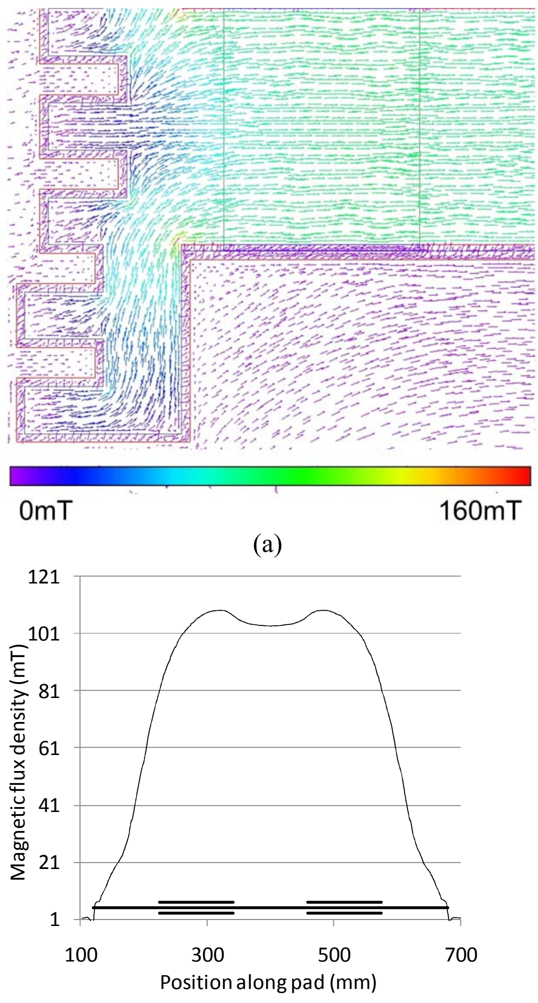
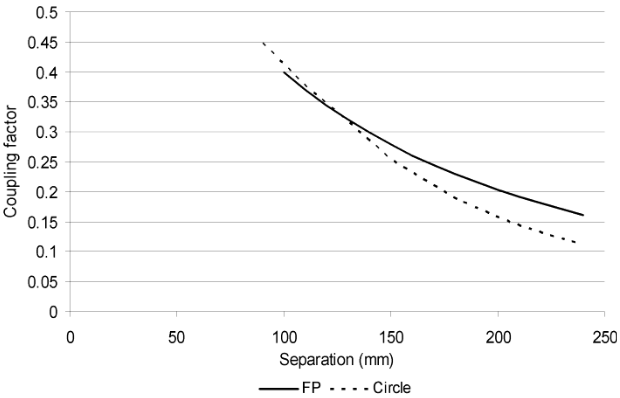


Fig. 5. (a) Flux density vector plot (b) Flux density through centre and along length of the track pad.

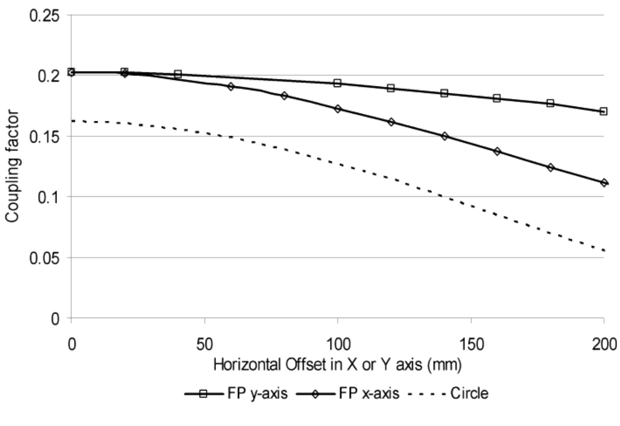
cost and reduce stored energy to a minimum for safety. As a result, the input voltage to the inverter bridge is a rectified sinusoid that is further amplitude modulated by the inverter switching pattern that is used to create an approximate sinusoid. Harmonics are filtered by the LCL network, as such RFI is not an issue. This double modulation results in peak currents that are twice as high as the RMS current. The operational flux density will be approximately 220mT in the centre of both coils. The ferrite material used is type N87 that has a saturation flux density of ~400mT. Although hysteresis losses are high at such densities at a frequency of 20kHz, this is not a major concern because the volume of ferrite where the flux density is greater than 200mT is small. There are four small areas where the wings join the flux pipe creating a sharp corner resulting in an increased flux density however this is also unlikely to present problems.

The graph in Fig. 5(b) shows the flux density along the middle of the pad. The position of the ferrite and coils are illustrated on the bottom. The slight drop in flux density in the middle of the pad is due to leakage however this is not significant in its operation.

The graph in Fig. 6 (a) shows the coupling factor of the flux pipe and circular pads as the separation is varied from 80-200mm. The circular pad performs better at relatively low separations of 120mm due to its larger surface area. The nature of a circular pad means its entire surface produces a relatively uniform flux pattern and given it has 1.7 times the area of the flux pipe, the coupling is significantly better. The flux density reduces rapidly as shown by the steep gradient of the coupling curve as separation increases. This results in significantly lower coupling at practical separations of around 200mm.



(a)



(b)

Fig. 6. Profiles of circular and flux pipe pads (a) vertical and (b) horizontal at 200mm separation

TABLE I
COMPARISON BETWEEN CIRCLE AND FLUX PIPE

Parameter	Circular pad	Flux Pipe	Unit
Number of Ferrites	36	34	
Length of Wire	31	13	m
Area	0.38	0.22	m^2
Coupling @200 Sep.	0.16	0.2	M/L_2
P_{su} @ 200 Sep.	775	1211	VA
P_{su}/Area @ 200 Sep.	2039	5505	VA/m^2
P_{su}/Vol. of Fe @200 Sep.	0.51	0.85	VA/cm^3

Horizontal profiles for both topologies at 200mm separation are compared in Fig. 6 (b). The flux pipe makes the PU polarised and two profiles are provided to characterise its performance. The length of the pad is assumed to be the x-axis and offsets that have x and y components lie in between the respective orthogonal profiles. The flux pipe has extremely good tolerance to misalignment in the y-direction however the rate of reduction in coupling in the x-direction is similar to that of a circular PU. This presents no problem if the pad is oriented correctly on the vehicle chassis and a suitable guidance method is used to constrain movement. Without any guidance constraints, the flux pipe allows a charge power of 2kW within a ~200mm radius of the pad centre, which is sufficient for an unguided EV. A comparison between various parameters of the two topologies is shown in Table 1. Both pads were excited with 23A at 20kHz. The flux pipe offers far better coupling with a lighter and more cost effective design. Copper losses are significantly reduced since only 42% of the length of wire used in a circular pad is needed. The ferrite is being utilised far more effectively in the flux pipe and the power transfer density is significantly higher allowing compact pads that simplify mounting on EVs. The flux pipe is 4mm thicker than the circular pad due to the winding of the coil.

VI. CONCLUSIONS

The merits of an IPT EV charging system are safety, convenience and reliability however the feasibility of implementing such a system largely depends on the performance of the power pads that must be as efficient and cost effective as possible. The coupling factor is a good metric for comparing different pad designs and is easily measured with an LCR meter. Conventional inductive couplers are based on circular designs where the fundamental flux path height is proportional to one quarter of the pad diameter. Consequently, extremely large pads are required to get the desired coupling factor of 0.2 at 200mm. An ideal bar type pad has a flux height proportional to one half of the pad length however realizing the necessary coupling factor is not practical with a simple winding due to the large pad inductance and length of Litz wire required. A flux pipe has been developed that has the advantages of an ideal bar topology with minimal inductance and material requirements.

Two approaches were used to create the desired flux path, namely dual coils magnetically in series and aluminium shielding plates that ensure flux leaves or enters the pad at the Tx and Rx surfaces. The flux pipe outperforms the circular topology in every aspect shown and has extremely good coupling with minimum material requirement. The polarised flux pipe offers far better tolerance to misalignment than the 700mm circular pad and meets the tolerance requirements for an EV if it is constrained in one direction. As a result of the research presented in this paper, it is possible to implement a practical IPT system for recharging EVs with the confidence that the design is theoretically the most optimal since it is based on an ideal flux path.

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