Practical Considerations for Designing IPT System for EV Battery Charging

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***Abstract-* The paper proposes a hands-free Inductive Power Transfer system for charging the batteries of an Electrical Vehicle. A typical system comprises a power supply, a transfer pad on the ground, a receiving pad on the vehicle together and a power regulator. This paper describes the design of the power regulator which must ensure continuous power flow at high efficiency despite wide separation between the charging pads as a result of variation in the vehicle to ground heights. The paper also discusses the need to meet new and stringent electromagnetic field exposure regulations. Measurements show good efficiency across various separations and emissions compliance providing the pad is placed underneath the vehicle.**

Keywords-Hands-Free, Inductive Power Transfer, EV Battery Charging

I. INTRODUCTION

Since the latter half of the 20th century, there have been increasing demands on developing vehicles utilizing an environmentally friendly power source to replace the conventional internal combustion engine (ICE). Electric vehicles (EV), as one of the candidates to replace the ICE, have been under a continuous research and development cycle for decades. One major hurdle for EVs that must be overcome to be widely accepted by the public is a way to transfer energy to the onboard storage safely, and conveniently. At present the majority of available EV battery charging systems are conductive plug-in, which are inherently unsafe due to the exposed electrical terminals. One solution to this is to use a hand-free Inductive Power Transfer (IPT) system. Such systems have been proposed in the past [1], however a paddle system as proposed still requires plug to be inserted into the vehicle. This system discusses here only requires a vehicle to be parked over a charging pad with reasonable alignment to a second receiver pad on board, the details of which is discussed later.

A typical IPT system is shown schematically in Figure 1. As shown there are two conceptually different parts to the system with galvanic isolation between them: a power supply takes power from a utility and converts it to a current at VLF frequency (in the range 5-50 kHz) which is used to energise an elongated loop or a lumped coil called a track, and one or more pick-ups couple power inductively from the track.

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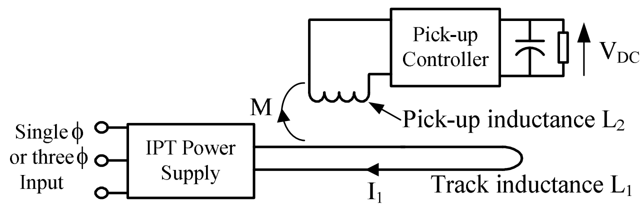

Fig. 1. A typical IPT system

These pick-ups are tuned or compensated with capacitors and power from them is then regulated and available to drive loads as required. A single power supply can drive many pick-ups provided that the operation of one does not compromise the flow of power to any other, and that the total power does not instantaneously exceed the output power capability of the power supply. As there is no physical contact between the primary and secondary coils, an IPT system is very resistant to chemical, water and dirt, and the secondary pick-up has good lateral movement tolerance relative to the primary track [2]. For these features, IPT systems are now widely used in a variety of industrial applications. Examples include, material handling systems, clean room applications and battery charging for people movers and electric buses [3-6]. However, there are a few practical issues that need to be considered in order to utilize IPT systems in domestic EV battery charging. Two in particular are: human exposure to magnetic fields and a secondary pick-up controller with the capability to handle height variations between the primary and the secondary pads. Both are discussed later in this paper.

The focus of this work is a 2kW IPT system with 230V utility input for domestic EV battery charging applications where an IPT primary and secondary coil configuration, referred as charger pad, discussed by [5, 7-9] is used. The charger pads are designed to be installed underneath the vehicle. In this system, a single phase power supply with minimal DC energy storage and amplitude modulated track current presented in [10] is used because of it has good input power factor (pf = 0.94). A new IPT pick-up control strategy, termed a multi-path pick-up, is presented. This pick-up controller is constructed using multiple LCL networks one of which is discussed in [11]. By controlling the each network individually, the output power can be regulated with variable coupling between the charger pads. Here, a design methodology is presented along with practical results.

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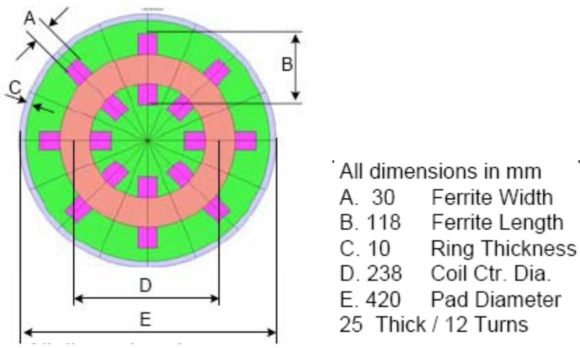


Fig. 2. Charger pad layout

Displacement from pad (mm)	Flux Density (µT)
0	317.5
20	131.3
40	57
60	30.2
80	17.8
100	11.3
120	7.5
140	5.6
160	4.1

Table. 1. Simulated results magnetic flux density horizontally away from the edge of the charger pad

II. PICK-UP CONCEPT FOR EV BATTERY CHARGING

A. *Pick-up Charger Pad Magnetic Structure*

As mentioned earlier, one of the practical issues for utilizing IPT EV battery charging systems for household applications is the leakage flux around the charger pad. At the frequency used here the limit of general public exposed to magnetic field intensity is regulated in Europe to be 6.25 µT by ICNIRP [12]. Therefore, the design of the magnetic structure for this application is important in order to constrain the leakage flux outside of the pad to be within the regulations. The structure of the primary and secondary charger pads chosen for the proposed EV battery charging system is shown in Figure 2. This distributed ferrite structure was suggested for EV charging applications [9]. With this structure, most of the flux is contained within its cylindrical area. Outside the charger pad the magnetic flux density drops rapidly. The simulation results are shown in Table 1. The results suggest that at 140 mm away from the edge of the charger pad, the flux density is already below the limit of 6.25 µT. This battery charging system is designed to be installed underneath the vehicle, and consequently the magnetic flux density outside the vehicle area will easily meet the 6.25 µT reference level specified by [12].

B. *Concept of Multi-Path Pick-up*

With the charger pad installed on an EV for domestic battery charging, the height clearance may vary according to various factors including tyre pressure and vehicle loading. These changes of height will alter the coupling and the mutual inductance between the charger pads. Thus, this variation needs to be taken into account in the design of the battery charging system. For the charger pad in Figure 2, a height variation from 50 mm to 85 mm is allowable. The practically measured coupling and the mutual inductance of the charger pads for a height between 40 mm to 140 mm is shown in Figure 3. According to the graph, the mutual inductance varies from 23µH to 12µH with height displacement changing from 50 mm to 85 mm.

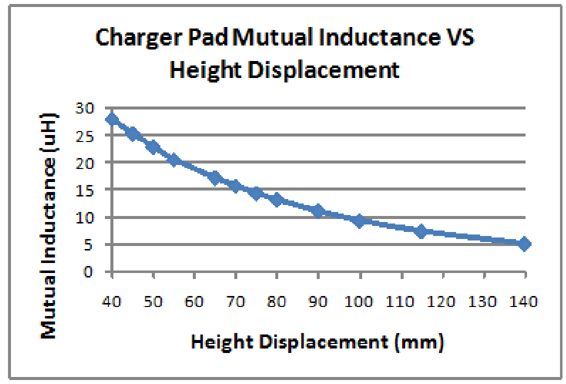


Fig. 3. Mutual inductance between the charger pads

This variation in mutual inductance is problematic for current existing IPT pick-up controllers [13-15], which are normally designed with a fixed air gap. Three IPT pick-up controllers, LC series tuned, LC parallel tuned and LCL tuned topology, are shown in Figure 4 and their reflected impedance onto the primary track is expressed in equations 1, 2 and 3, where X is the characteristic impedance of the LCL network [13]. Both the LC parallel tuned and the LC series tuned with

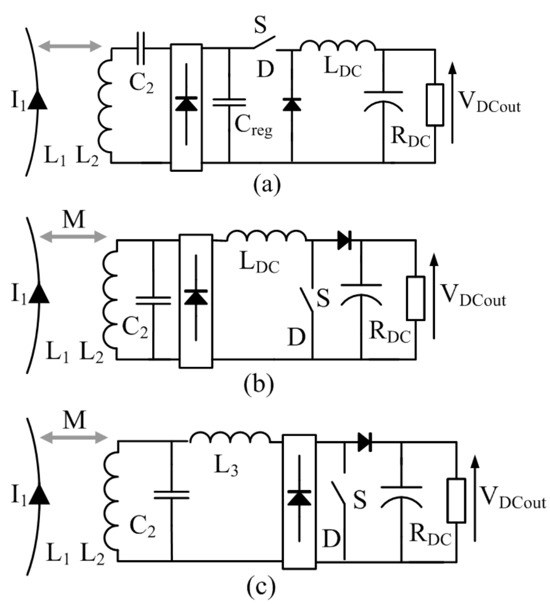


Fig. 4. (a) LC series tuned pick-up, (b) LC parallel tuned pick-up and (c) LCL tuned pick-up

switch mode controller can operate in either fast or slow switching modes. Both have their strength and weakness [14, 15]. Slow switching is however more practical for power ratings beyond 1 kW because of its improved efficiency [16]. In such slow switching controllers, the duty cycle D is either 0 or 1. If however the mutual inductance varies by a factor of 2, the instantaneous power drawn by the pick-up can be 4 times higher than the nominal value. This instantaneous power required by the pick-up will overload the power supply. The problem could be solved using a two way communication system to vary the primary track current to limit the power transferred to the secondary. However, if the supply is operated with a mutual inductance variation of 2, the track current will also need to be varied by 2 to compensate it. This makes the power supply difficult to design because the H bridge in the power supply will need to work with narrower duty cycle so the semiconductor switch will need to be over rated.

$$Z_{Equiv.Series} = \frac{\pi^2}{8} \cdot \omega^2 M^2 \cdot \frac{D^2}{R_{DC}} \tag{1}$$

$$Z_{Equiv.Parallel} = \frac{M^2}{L_2^{\,2}}\left(\frac{\pi^2}{8} R_{DC}(1-D)^2 - j\omega L_2\right) \tag{2}$$

$$Z_{Equiv.LCL} = \frac{8}{\pi^2} \cdot \left(\frac{\omega M}{X}\right)^2 \cdot R_{DC} \cdot (1-D)^2 \tag{3}$$

For these reasons, a new pick-up controller, termed a multi-path pick-up, is proposed and shown conceptually in Figure 5. The pick-up inductor L_2 is fully series compensated by C_2 at the operating frequency. This way the voltage level that appears across the AC voltage bus is essentially the same as the induced open circuit voltage ($V_{oc} = j\omega M I_1$) in inductor L_2. A number of identical LCL networks, shown in Figure 6, are connected to the voltage bus and each network is connected in parallel after their bridge rectifier to deliver power to the load. Thus, each channel is designed to take a portion of the total output power. Each LCL network can be individually switched on and off. Thus by controlling the number of active LCL networks based on the measurement of the magnetic coupling between the charger pads (as indicated by V_{oc}), the power transferred to the secondary can be regulated as described by (4), where n is the number of active LCL networks. Although

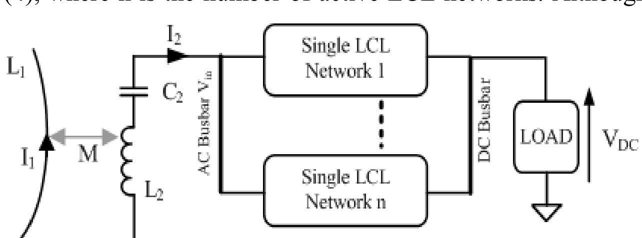


Fig. 5. Conceptual diagram of multi-path pick-up

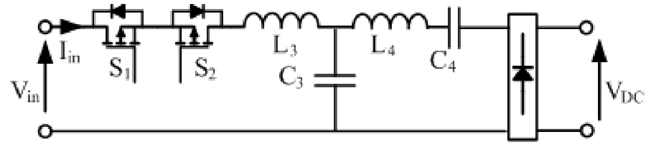


Fig. 6. Single LCL network

the total number of passive components required by the multi-path pick-up is greater than that used in a conventional IPT pick-up controller; each LCL network is only carrying a portion of the designed output power, so the components are relatively small and the total installed VA of the component is the same.

$$Z_{Equiv.Multipath} = \frac{8}{\pi^2} \cdot \left(\frac{n\omega M}{X}\right)^2 \cdot R_{DC} \cdot \tag{4}$$

III. DESIGN AND CONTROL OF MULTI-PATH PICK-UP

The design methodology for an LCL pick-up was discussed in [11]. The same procedure can be applied here to design each LCL network. The multi-path pick-up output power is then described by (5), where n is the number of active LCL networks. A feature of the LCL network is that the input current I_{in} ($=2\sqrt{2}\ V_{DC}/\pi X$) is constant providing V_{DC} is controlled constant by suitable action of the switches. The first ($2\sqrt{2}/\pi$) factor comes from the operation of the power supply that causes the track current to be modulated at double the mains frequency [10]. This modulation directly affects the average open circuit voltage.

$$P = \frac{2\sqrt{2}}{\pi} \cdot n \cdot V_{in} \cdot I_{in} = \frac{2\sqrt{2}}{\pi} \cdot n \cdot V_{in} \cdot \frac{2\sqrt{2} V_{DC}}{\pi X} \tag{5}$$

When the pad is at constant height, the power output can be simply varied by changing n. At maximum height, all LCL networks will be active. As the pad height decreases M increases and n must be reduced to maintain power, but each LCL network now can output more power directly related to the increase of M. This increased rating must be taken into account in the design, however the average power delivered by each LCL network may be lowered by interleaving. [17]. The ideal number of components is determined by how much M is allowed to vary, complexity, control requirements and cost.

In the application discussed here, a decision was made to use a 5.5 multi-path pick-up network. The half network is used to enable improved output power resolution and control, ie: it allows a 10% step change instead of 20%. A simple graphic, shown in Figure 7, is used to assist the determination of the number of networks required for a particular design. At the maximum spacing (M = 12µH), all 5.5 networks are needed to be on to deliver the required output power. As the charger pads move away from each other, the mutual inductance drops. Thus, the pick-up controller will not be able to deliver

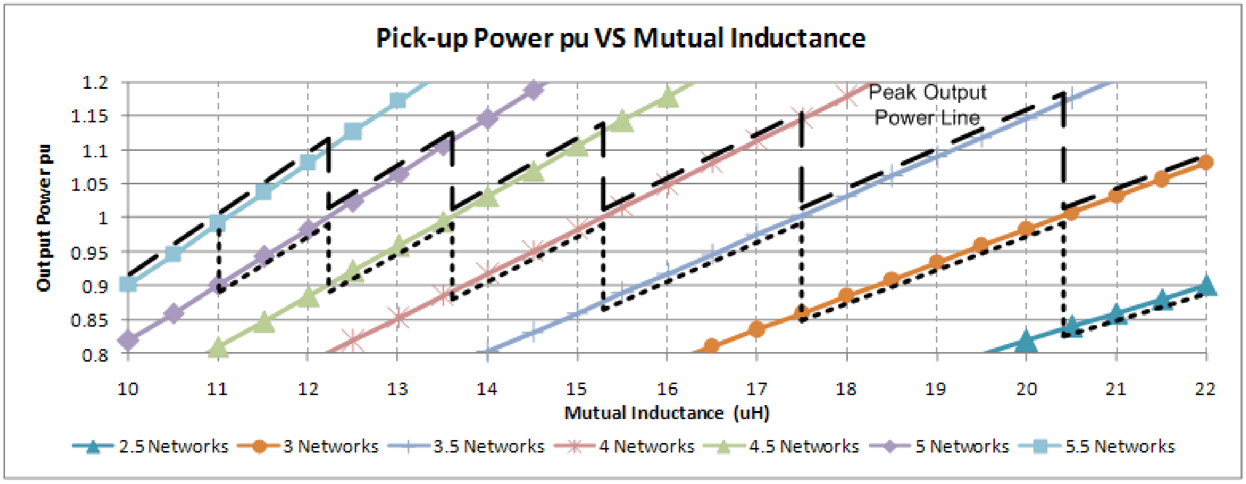


Fig. 7. Ideal multi-path pick-up output power VS Mutual inductance

the rated power. As the charger pads move closer, the number of networks may be reduced in half steps as shown in Figure 7 to counter the increase in mutual inductance. The dashed line is the controlled peak output power of the pick-up with variation of mutual inductance and the dotted line is the pick-up output power with one half network less than the dashed line. It is important to make sure the peak of the dashed line does not exceed the maximum power capability of the IPT power supply. The instantaneous output power cannot be kept at the nominal 2 kW level. Instead average power is controlled constant, using a similar hysteresis control technique to that presented in [14] by controlling the number of active networks to be in between the dashed line and the dotted line shown in Figure 7. For example, with a mutual inductance of 16 μH between the charger pads the number of active networks will be changing between 3.5 networks (output power = 0.92 pu) and 4 networks (output power = 1.05 pu) to give an averaged desired output power level.

As discussed in the earlier section, the power supply used in this EV charging system is a mains single phase input with minimal DC storage and amplitude modulated primary track current at double of the mains frequency. Since the multi-path pick-up requires to switching in and out of a half network to regulate the average output power it would be ideal to perform the network switching synchronised to the utility zero crossing to minimise the switching loss. This has the advantage that it minimises the distortion on the IPT power supply mains input

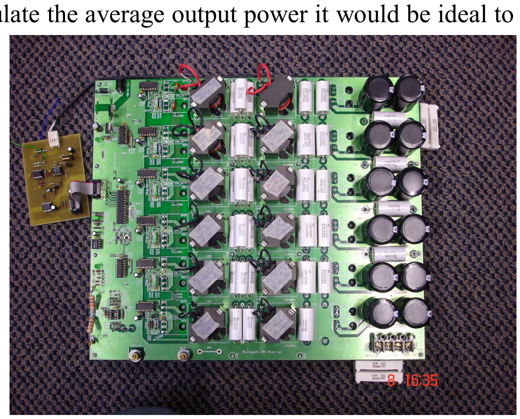
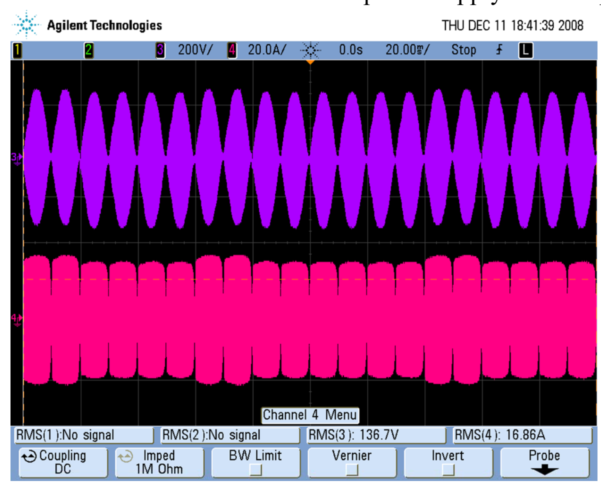
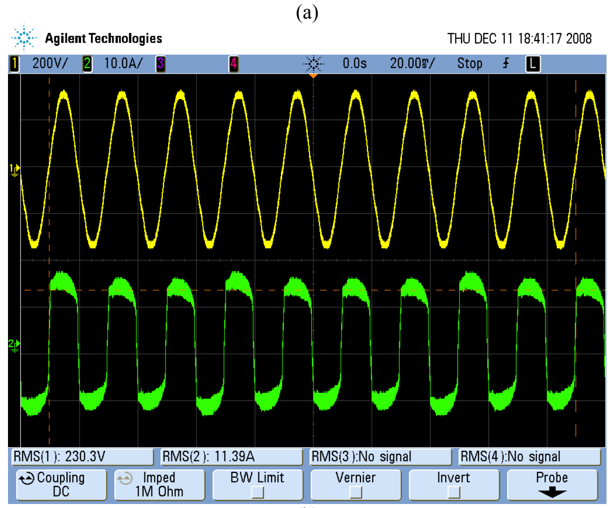


Fig. 8. Prototype of a 5.5 networks multi-path pick-up

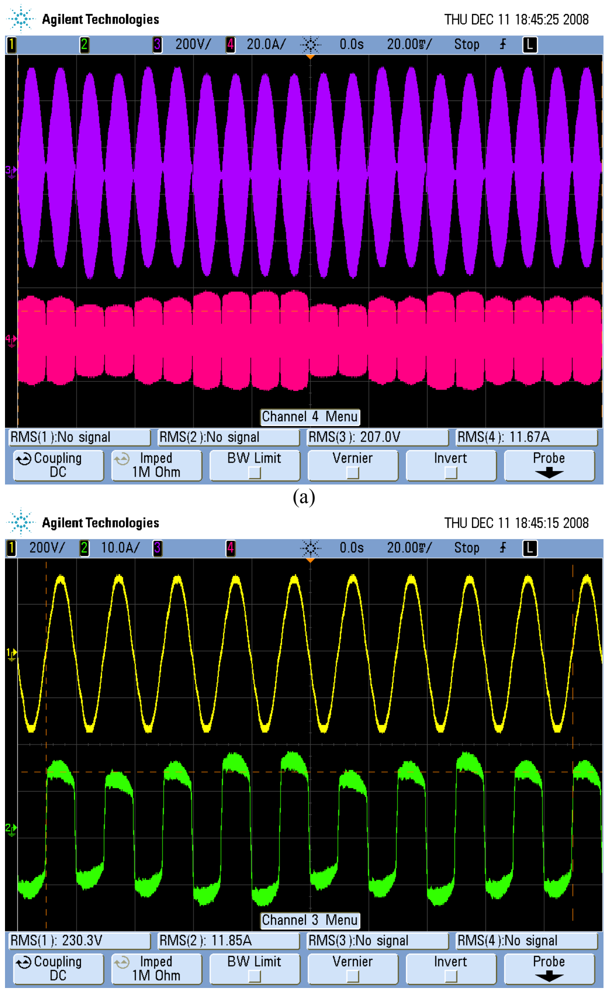


(a)



(b)

Fig. 9. Tracers from top to button are (a) V_{in} and I_2, and (b) Mains voltage and current with mutual inductance of 14.3 μH between the charger pads



(a)

(b)

Fig. 10. Tracers from top to button are (a) V_{in} and I_2, and (b) Mains voltage and current with mutual inductance of 22.8μH between the charger pads

current and maintains a good input power factor. Since there is only minimal DC storage in the primary power supply, any transient distortion occurring in the pick-up will easily reflect onto the mains input current. With a simple envelope detection circuit, the S_1 and S_2 in the designed controller are operated slowly at the zero crossing of the modulated track current to minimise switching loss and distortion.

IV. Practical Results and Discussion

A prototype of the 5.5 network multi-path pick-up discussed earlier was build and is shown in Figure 8. This prototype was constructed for experimental purposes, although the physical size was not optimised. Because each network is only taking a portion of the output power, it could be easily designed with surface mount semiconductors and easily set up for machine manufacturing. The multi-path pick-up has been tested on the proposed 2 kW IPT EV battery charger system, which has a variation of mutual inductance of 11 μH (12 to 23 μH) between the charger pads. Oscilloscope captures of the EV battery charging system outputting 2 kW are shown in Figures 9 and 10.

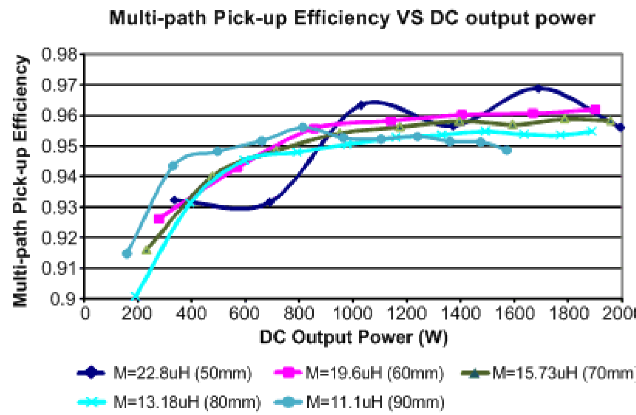


Fig. 11. Multi-path pick-up efficiency measurement VS output power

From Figures 9 and 10 (a), it can be seen that the half LCL network is controlled on and off in order to control the averaged output power to 2 kW. Because each of the LCL networks are switched on and off at the zero mains voltage, this switching action does not result in any observable transient in the mains current shown in Figures 9 and 10 (b). As a result, the mains input power factor is kept within 0.93 to 0.95 across all output power ranges. The efficiency of the multi-path pick-up for different couplings between the charger pads was measured and is shown in Figure 11. The maximum power efficiency and the part load efficiency of the multi-path pick-up is around 95 to 96 %, and the low power efficiency is above 90% for all practical ranges of power output.

V. Conclusions

For IPT EV battery charging system to be applicable, there are two main practical considerations: leakage magnetic flux magnitude and the variable mutual inductance between the primary and the secondary charger pads. A round charger pad structure is easily able to comply with the European ICNIRP regulations when placed under a vehicle under normal charging operation. A multi-path pick-up topology is able to regulate the output power with the mutual inductance varying within the designed range.

A 2kW 5.5 networks multi-path pick-up was presented in this paper. It is able to regulate its output power with mutual inductance between the charger pads varying from 12 to 22 μH. The multi-path pick-up achieved efficiencies at 96% at 2kW and above 90% for all output power ranges.

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