IPT Fact Sheet Series: No. 2
Magnetic Circuits for Powering Electric Vehicles

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Roadway Pad Development

Introduction

Inductive Power Transfer (IPT) systems for charging EV Batteries in-situ are gaining attention as they are wireless and do not have to be plugged in. These systems use two wireless pads – one on the underside of the vehicle and the other on the road surface underneath the vehicle – that are magnetically coupled to each other. This wireless power transfer uses inductive coupling under resonance with coils or multiples of coils with high native quality factor (Q_L). The coupling is a geometrical property of the magnetic and electrical circuits: better pads achieve coupling depending on their design and a poor design can never be adequately compensated but leads inexorably to a poor IPT system. Early commercial designs were developed in the 90's and have been improved over the past 20 years. This inductive coupling is known in the academic literature to be identical to strongly coupled magnetic resonance.

For efficient charging with minimal field leakage the car must be parked or positioned so that the two pads are in relatively close proximity to each other. Under these conditions a recognition system allows the two pads to communicate with each other such that ultimately the pad on the ground is 'fired up' and energy is transferred from the ground pad to the on-vehicle pad and thence to the battery. When the battery is charged the system disconnects; both the ground pad and the vehicle pad are shut down. In more complex situations the charger can also transfer power from the car to the ground pad and back to the utility and all such systems described following can be made bidirectional; however this action will not be explicitly discussed here.

Wireless charging via IPT can only occur if several conditions are met simultaneously:

- The pads must be compatible with each other
- The pads must operate at the same nominal frequency
- The position of the car must have the on-vehicle pad within the relative x, y, z, error that is allowable for this pad pair
- The communications protocol must be compatible between the two pads
- The power ratings and connections of the two pads must be designed to be compatible and at similar rating – a 100kW bus primary charger cannot be used with a 2kW secondary car battery connection with an expectation of high efficiency and low field emissions, although a 20kW primary system may be able to achieve good results with the same 2kW secondary if this is considered at the design stage.

If these conditions are met the charging pad on the ground can be turned on slowly and following reasonably stringent frequency and power checks the battery will begin to charge under the control of a Battery Management System (BMS) until the BMS indicates that no more energy is required and the BMS shuts the system down – or the car drives off and leaves the system to shut itself down. Any premature disconnection is essentially harmless with wireless charging as it does not cause physical damage. Furthermore the system automatically shuts down if there is an undesirable change in coupling between primary and secondary pads such as vehicle movement resulting in severe misalignment.

Compatible pad pairs that can perform this charging service are very special devices that have not been seen before. They are special because of the conditions they operate under and the coupling that is required. The ground pad must operate from a location where wheels from other vehicles may frequently run over it when it is not in use; from under the vehicle the primary pad must produce a high arching flux to link to the on-vehicle pad while not leaking flux into other parts of the vehicle, and any unwanted flux emerging from under the vehicle must be extremely small to meet ICNIRP guidelines. The vehicle pad (when not in use) is expected to be continually struck by objects from the road surface such as stones water mud and ice when the vehicle is in motion, yet must maintain its performance in spite of this, and couple power from the ground pad to the BMS with a magnetic efficiency in the high 90% range when required. The pads must allow coupling with an air-gap of as low as 100mm up to 300mm or more and they must survive the extreme conditions that can be found under a vehicle including temperatures from -20 ^{O} to +65^{O} C over a lifetime of several years. To meet these challenging physical requirements the pads must be made of materials that are very tough and resilient – for example polyurethane, tough plastics, rubber etc. but the flux linking requirements can only be met with special materials such as high frequency litz wire which is very fragile and highly permeable ferrite which is extremely brittle. Thus the physical construction of a pad is a compromise between fragile and tough, between flexible and brittle, between the high performing electromagnetic materials that can give the performance required and materials that can protect those electromagnetic components while they do it. A good pad design is one that can achieve this balance.

The overwhelming advantage of inductive charging is that because it does not have to be plugged in charging can occur in a wide range of places – in a garage overnight, at traffic lights, outside a shop, at a workplace, and many others, and this multiple charging keeps the battery in a high state of charge, operates it more efficiently, and extends its life. Indeed the tolerance over which charging is possible even extends to charging dynamically while the vehicle is in motion on a road – this is the ultimate range extender and gives the highest efficiency of any transportation system. Strings of pads down the centre of a carriage way are energized sequentially in synchronism with the passage of the vehicle over them so that the vehicle is powered from pad to pad at high efficiency with an essentially continuous supply of power.

This paper looks at the development of magnetic pad systems for the charging of all manner of roadway vehicles from private cars to public buses and trucks under stationary conditions. Here the evaluations are undertaken at 20kHz, given this was the industry norm for more than 20 years. However they are equally applicable to higher frequencies such as 85kHz (which is now the accepted standard for EV charging), since coupling factor is independent of frequency.

Charging is seen to be a special type of IPT operation where the end user is (as noted) the BMS that controls the actual charging of the battery. The paper does not cover dynamic charging though the pad systems may in fact also be serviceable here too. Rather the paper considers magnetic pads and pick-ups as developed in Factory Automation (FA) and in clean electronic Factory Automation (eFA) and builds on proven industrial success in materials handling to develop pads for (stationary) charging. These FA and eFA pads and controllers are used in more than 90% of IPT systems in present day applications and are widely accepted for their reliability and functionality. Starting from this background the paper then considers the special requirements for charging before discussing the specifics of FA and eFA systems, and then outlines how charging pads have been developed.

Requirements of an EV Charging System

The IPT charging system for an EV in its simplest form involves two pads: one travels permanently with the vehicle while the other may be duplicated and shared by other vehicles in a multiplicity of places most commonly in a home garage and at a place of work. Access to the pads may be omnidirectional where the vehicle approaches the pad from any direction, or more commonly from a preferred direction where charging is only possible from one direction. The ground pad would usually be connected to a power supply that is driven by a utility. The communications protocol that controls the charging process will allow matched and mismatched pads to charge providing the nominal frequency is identical and the design supports charging.

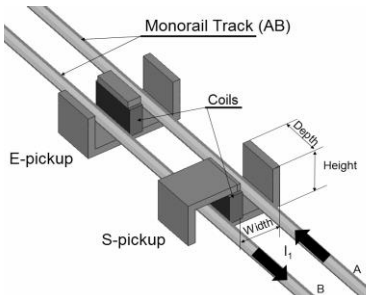
At Auckland University our pad designs have been developed based on our extensive background and experience with magnetic pad development with FA and eFA systems in the 90's followed by Automatic Guided Vehicle (AGV) and EV charging systems in the late 90's and early 2000's. The FA and eFA systems are characterized by operating on a monorail or floor track where several vehicles are on the same track at the same time. Here it is important that the power supply is not overloaded and that the system will decouple pads that might cause overloading. In a pad on pad situation with individual charging control such one to many power control is not essential, but the developed secondary regulation developed for these systems also offers significant advantages for efficient control of a one to one charging system while helping to ensure safe operation. Both are difficult to achieve if the control is only undertaken from the primary. In factory automation the cost is reduced by having no ferrite in the track, but ferrite is always used in the carriers and designed to couple with the best localised coupling factor possible – the pads are also essentially asymmetrical. The FA track guarantees close alignment between the moving pads and the stationary track and unused sections of track are still excited and still radiate magnetic fields but these are in controlled environments where personnel are trained to be aware of any risk. With EV chargers the situation is quite different as leakage fields must be contained within limits and any pads not covered by a charging vehicle must be turned off as the general public can be in close proximity to a vehicle being charged. Pads for FA and eFA are usually less than 2.5 kW and typically less than 1 kW while EV charging may be as low as 2 kW in a home connection but is usually 3.3-6.6 kW in a commercial setting, and higher power charging for light duty trucks and car share programs may be as high as 22kW.

Materials Handling with monorails

Our Materials Handling for Monorails

In the majority of materials handing applications, the pick-up is mounted on a moving unit (bogie) and its output power is subsequently converted to a form useful to drive one or more motors that enable lifting operations or drive a travelling motor to move the bogie along a primary track. In order to save cost and ensure that long track lengths can be driven, the track in a materials handling application has no magnetic material to enhance the power transfer. As such each coupled pick-up uses magnetic material such as ferrite to improve the local coupling and hence the power transfer. For monorail systems the movement of the system is highly constrained and consequently the magnetic material can be designed to extend partly into and around the track wires to improve the coupling. The majority of such industrial systems use U, H, or E shaped pick-ups as these pick-up shapes were readily available and easy to fit into existing structures. With the advent of 3D finite element modeling new pick-up shapes have been investigated. Of these the S-pick-up shape (shown alongside the traditional E shaped pickup in Figure 1) has been shown to have significantly higher power transfer capability than either the conventional E or U shapes (by a factor of 2 for the same volume of ferrite as the E pick-up). Uptake by industry of the S pick-up has been slow because this design requires significant modification to the monorail support system.

(a)



(b)

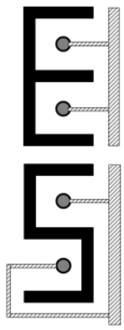
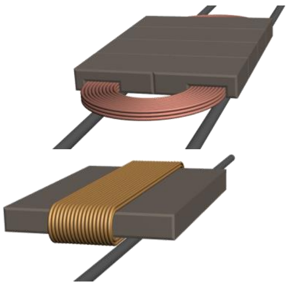


Fig. 1:
(a) The E and S power pickup's as positioned along a track section
(b) Cross sections of pick-up and track with added support structures

Our Materials Handling for AGV's

Pick-ups which are used for AGVs, and other forms of vehicular systems commonly move on and above surfaces which must allow some freedom of movement. Consequently the track is usually buried and pick-up designs are normally flat E or I shaped as shown in Fig. 2(a) and Fig. 2(b).



(a)

(b)

Fig. 2. Common pick-up for AGVs with constrained movement (a) Flat-E, (b) Flat-bar pick-up.

Here bi-polar (rather than uni-polar) tracks are preferred in commercial applications as they have a lower inductance with less unwanted emissions. The flat pick-up designs and coil placement of Fig. 2 are separately optimized to capture either the vertical (Fig. 2(a)) or horizontal (Fig. 2(b)) component of flux around the 2-wire primary cable, and are shown here in the position which would enable them to capture the maximum flux for a given height. With single phase bi-polar track systems, null points exist in the power profile irrespective of the magnetic component chosen. For the vertical pick-up, power-nulls exist above each of the conductors but a maximum is in the centre where it captures flux contributions from both conductors. The horizontal I shaped pick-up has a power-null at the centre of the track, and is at a maximum directly above each conductor. In practice both are sensitive to any misalignment, however the vertical pick-up is preferred as it couples more power but it is most sensitive to movement. Typical air-gaps tolerances of 10-20mm are required in these applications and as a general rule these systems only achieve lateral tolerances to misalignment (10-20mm) commensurate with the height making alignment difficult.

There are a number of ways in which the tolerance to misalignment may be improved but the simplest uses a single phase track and two pick-up coils, that are in quadrature with each other, by carefully matching the pick-up to the track spacing. This significantly improves the coupling between the pick-up and track while allowing improvements to lateral tolerance compared to other approaches. As described, such a pick-up enables power to be coupled from both the vertical and horizontal components of flux, each of which exist above both single or multiphase track systems, so that the tolerance and performance of the pick-up receiver can be improved. An example of such a magnetic pick-up is shown in Fig. 3. Magnetic design and computer optimization have been employed to ensure the best coupling of the available vertical and horizontal flux components, while the controller can be simply modified to ensure good steady state and transient operation and efficiency. Surprisingly the impact on the power supply tuning and operation is improved as a result of using a quadrature receiver, over the "simpler" designs shown in Fig. 2 with little or no loss in efficiency; though additional tuning electronics and a rectifier must be included. The only difference between a standard pick-up controller and the controller required for a quadrature pick-up is that here two windings are placed on the pick-up receiver and these are individually tuned, rectified and added before being controlled on the load side. The position and size of the windings are clearly shown in Fig. 3.

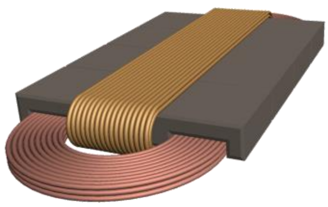


Fig.3. Example of a modified Flat E with both vertical and horizontal flux sensitive coils.

When used on a simple 2-wire track, maximum output from the horizontal coil occurs when the vertical coil is at zero output and vice-versa. Rated power transfer can be delivered with 600% improvement to the lateral tolerance of the pick-up receiver for horizontal or vertical coils alone without changing the primary track or power supply. With a three phase track topology this improvement can be increased further by as much as another three times, but the power supply and track will be more complex and on a specific performance basis it is usually not justifiable.

Our Track-less Floor Mounted Charging Systems

Lumped charging systems for higher power without a track have also seen development over the past two decades, with plug-in chargers being replaced by plug-in inductive systems. This has been followed by hands-free solutions that have met the air-gaps and tolerances required by robots and the like, that can approach a pad on the ground from any direction, and take power from it. This is the closest application that exists to EV charging. In such applications the primary and secondary magnetic systems are often very similar and generally both use ferrite to enhance power transfer. As a consequence, the demands on the supply are more challenging as there can be considerable lateral and vertical misalignment between the pads. These variations change L_1 and L_2 and the mutual inductance M so that mistuning is inevitable. With larger air-gaps the percentage variation in inductances is usually small and therefore higher operating Q's (3-10) are acceptable, while at smaller air-gaps the coupled power is usually sufficient that operating Q's of less than 1 may be enough and give the system a wider bandwidth in spite of greater mistuning. The variations make power transfer challenging, and in consequence most IPT charging systems have one power supply for each coupled load, so that the primary current and frequency can be adjusted to compensate.

As described in the literature, the power output of an IPT system may be quantified in terms of V_{oc}, I_{sc} and the operating Q_2 of the secondary circuit. With lumped systems it is helpful to rewrite this in terms of the VA at the input terminals of the primary pad ($V_1 I_1 \equiv VA_1$), the effective transformer coupling coefficient (k) of the two magnetic (primary ground and secondary vehicle) pads and the operating Q_2 of the secondary:

$$P = V_{oc} I_{sc} Q_2 = V_1 I_1 k^2 Q_2$$

The coupling coefficient k provides a direct measure comparing the magnetic properties of different pad topologies and can be easily determined using measurements taken with an LCR meter. When comparing topologies the secondary operating Q_2 can be temporarily ignored to decouple the magnetic design from the output power. In practice the pad input voltage is often constrained by regulation, limiting the VA of the primary. Consequently, the uncompensated power ($P_{su} = V_{oc} I_{sc}$) is highly dependent on k and designs that have maximal k at a given air gap are preferable.

Stationary EV Charging Systems

EV charging systems can now be seen to be very similar to trackless floor mounted systems as above but the power requirements are significantly higher, the environment is more stringent and the misalignments allowed are far larger by factors of 10 or more times. At present EV and PHEV manufacturers are interested in smaller vehicles with low ground clearances giving air-gaps between the primary and secondary pads as small as 80mm and as large as 120mm. The difficulty in making such systems and making them small is that there is an implicit change in the input VA with movement or misalignment as the inductance varies with the pad position. In practice, the input VA can be changed by adding series capacitance to the primary pad to lower the inductance seen by the supply however the amount that can be added is small as it also increases the tuning sensitivity. As described in the literature, the peaks in P_{su} and k do not usually occur at the same point in a design and selecting a pad that meets performance requirements (e.g. 7kVA) typically requires a compromise between k and the VA to drive L_1.

In these larger systems there is a fundamental change in the ferrite shapes that can be used. In a monorail for example fingers of ferrite essentially wrap around the track conductors leaving a small air-gap that can be used to assist in assembling carriers on the track. The flux in this air-gap is the working flux for the pick-up and it is characterized in that virtually all of it encloses the track conductor(s). However in large EV systems the ferrite is commonly a flat sheet or a large ferrite part and the concept of wrapping it around track wires is not helpful. Coils wound on these large ferrite sheets produce flux paths commonly on both sides of the ferrite and one of these flux patterns may be the required one while the alternative flux paths are not useful. Thus for example a solenoidal coil wound on a rectangular sheen of ferrite will have a flux pattern on both sides of the sheet making 50% of the flux paths useless. A much better pick-up or pad system will have flux on only one side of the sheet – called a single sided coil - where all of the flux is useful and the inductance of the coil is essentially improved by not including all the unwanted leakage flux.

There are basically four methods by which this unwanted flux can be removed:

1. Screen the unwanted flux out using a metallic sheet
2. Use a ferrite mirror to reflect the back flux to the front giving twice the flux on the correct side
3. Use a current carrying wire to deflect the flux away from where it is currently causing a problem
4. Use other coils in the area to modify the flux patterns and produce a better flux pattern.

The simplest way, method 1, is to block the unwanted flux with a sheet of aluminium or copper but this is very lossy and the copper or aluminium may get rather hot. Nonetheless this method is widely used because of its simplicity. Method 2 using a ferrite mirror is an excellent method but needs sheets of ferrite that are fragile and expensive. Here for example a planar Archimedean spiral can be placed on a flat plate of ferrite to produce a flux pattern on the same side as the coil with no flux on the obverse side.

Method 3 using a cancellation technique is commonly used for low level leakage flux where a current carrying wire can be used to deflect unwanted flux to a non-critical area. Method 4 is perhaps the most elegant of all but is very difficult to do. Here unwanted flux from one coil may be cancelled by flux from a different coil to eliminate the problem. There are few examples of this method.

Examples of pad system for EV charging systems

Circular (non-polarized) pads/couplers

In the early 2000's, non-polarized magnetics normally in the shape of a circular design were the most common topology used for EV charging – these are essentially derived from gapped pot cores. New designs use ferrite disks and spokes and focus on optimizing the use of ferrite and its layout – for example a pad measuring 700mm in diameter using readily available I-93 cores which are shaped as an I-bar and have dimensions 93mm x 28mm x 17mm (3 per radial strip) with a layout similar to that shown in Fig. 4 has a native Q_L of 291 at 20 kHz and an inductance of 542uH. This Q_L value gives a loss of 124W when driven with a current (I_1) of 23Arms. The loss in the vehicle pad is often lower as the vehicle pad usually operates at a lower current. These pads use methods 1 and 2 combined to achieve flux on only one side of the pad.

The relationship between the size of a pad and its ability to throw flux to a secondary pad placed above it has been explained using the concept of fundamental flux path height and is illustrated in Fig. 4. As shown the fundamental flux path height (Pz) is proportional to half of the ferrite length which is only one quarter of the pad diameter (Pd/4).

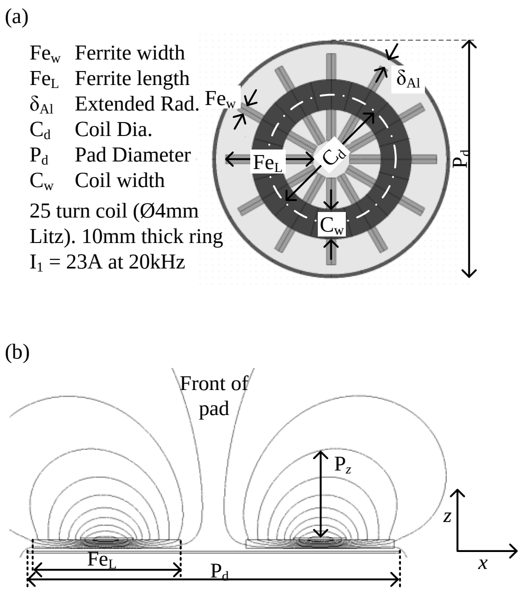


Fig 4. (a) Typical layout of a circular power pad (b) typical fields

Polarized couplers: Solenoid

Polarized couplers were developed and used in the 90's for monorail automatic guided vehicle (AGV) applications and also used in early EV charging developments in people movers at Whakarewarewa in New Zealand.

Consequently, various polarized solenoidal couplers were investigated and developed as early as the mid 90's with improvements in the mid 2000's based on shaped bar ferrites. Such pads have a defined north and south pole created by wrapping a flat coil around a flat ferrite structure as shown in Fig 5(a). As such these pads are essentially flattened solenoids. The distance between the end north and south poles and the size of the poles are each carefully designed based on application. An example of this is shown in Fig. 5(b) where two coils are used in parallel to direct the flux from one pole though the ferrite core to the opposing pole. Alternative designs use a single coil if appropriate. The natural field produced from this structure without any added aluminum or copper shielding is shown in Fig 5(c). As the centres of the poles are separated (approximately) by the length of the pad, these fields are much higher than those of the non-polarized designs, however flux is also naturally produced on both sides of the pad which must be avoided. As such method 1 is used with an aluminium or copper sheet covering the entire back structure (optionally another aluminum sheet covering the upper coil portions may also be used as shown in Figs 5(a) and (b)) so that only one side of the end poles is exposed to help direct the flux towards the other magnetic pad resulting in essentially single sided fields as shown finally in Fig 5(d). These shields prevent the flux from exiting the back of the pad and presenting a problem within a vehicle or causing heating of nearby objects. Without the back shield the pad has a Q_L value of typically 210 at 20kHz – and with the added aluminium shield surrounding the ends and back this Q_L can drop to as low as 90 as a result of the eddy current losses induced in the shield. Even with the shield in place, this pad topology naturally generates strong horizontal flux paths out each end of the ferrite that are not easily absorbed and this means that the orientation of this coupler on a vehicle must be carefully considered. With the necessary shielding it is difficult to achieve magnetic efficiencies in the high 90's, as is possible in the following improved topologies.

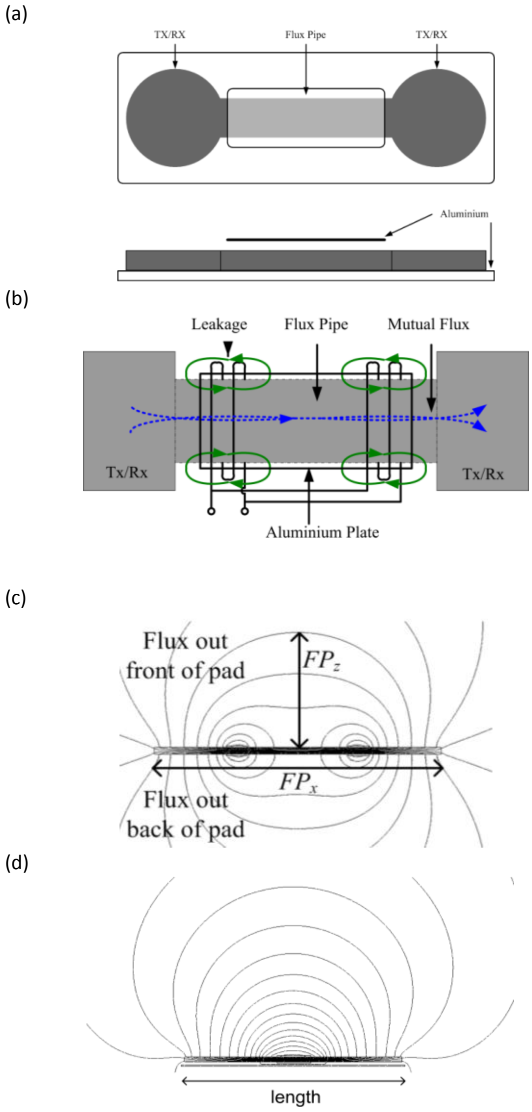


Fig 5. (a) Typical layout of a polarized solenoidal pad (b) with multiple coils rather than a single coil to create the flux pipe, (c) typical fields without shielding (d) single sided fields when aluminum or copper shield plates are added at the back.

Polarized Couplers: Double D

An improved single sided polarized flux pad topology is shown in Fig. 6. It has been labeled as Double D (DD) because of the ideal D shape of the coils sitting on the ferrite base. There is no reverse flux here as the ferrite operates as in method 2 to eliminate it by reflecting it upwards. The improvement eliminates the unwanted rear flux paths by placing two coils above (rather than around) the ferrite strips. The ferrite channels the main flux behind the coils and forces the flux to exist on one side only. The height of the intra-pad flux ($\emptyset_{ip}$) is controlled by adjusting the width of the coils in the shaded area of Fig. 6, to create a "flux pipe" between coils a and b. The fraction of flux $\emptyset_{ip}$ that couples with the secondary pad is mutual flux ($\emptyset_M$), therefore the section of the coil forming the flux pipe should be made as long as possible. Conversely, the remaining length of the coil should be minimized to save copper and lower the coil resistance. An example DD pad with a primary surface area of 0.32m^2, has an inductance of 589uH and a Q_L of 392 at 20kHz. These figures are so close to those of the previous 700 mm circular pad that direct comparisons are possible.

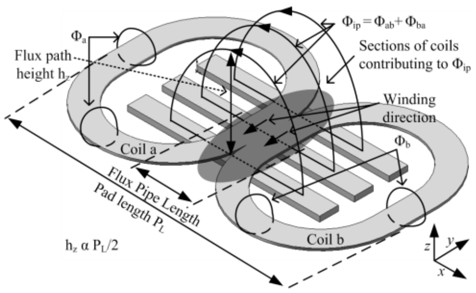


Fig. 6. A simplified model of a DD pad with main flux components Φa, Φb and Φip, produced by coil a, b and mutual coupling respectively.

Multi-coil Polarised pads

As a secondary (vehicle) pad, DD coils can only couple horizontal flux components when centered on a primary, whereas circular pads can only couple vertical flux components when centrally aligned. A new class of multi-coil pads were constructed which, similar to the quadrature designs for materials handling application, are sensitive to both vertical and horizontal flux components at any point in space (although because of their design they are also polarized). In consequence they can be made completely interoperable any single, two-phase or 3-phase coupler.

Naturally these Multi-coil couplers can also be used as the primary (ground) pad and thereby used to couple to any range of secondary (vehicle) pads. To achieve this flexibility in operation a second synchronized power supply is required to enable the independent coils to be driven separately, but then it enables simple circular, solenoid or DD pads to be used on the vehicle side under stationary charging conditions. Under these conditions either polarized or non-polarized flux patterns could be created to suit the secondary topology, and the driving mode can be modified based on the alignment of the vehicle to improve the power transfer under misaligned conditions.

These changes require no additional electronics or passive tuning, but rather a variation in the phase of the driving currents under software control. When operated as a polarized coupler they achieve coupling factors similar to other polarized pads (with a similar area) coupling to any given secondary, whereas when operated in circular mode the coupling factors are similar to non-polarised pads. In either operation mode the quality of the pad is naturally high given the pad generates single sided fields. As such multi-coil pads can be used in a wide range of applications and offer a variety of features not found anywhere else.

As a secondary vehicle pad, these new pads use two completely independent windings to capture all of the available flux in the secondary ferrite, enabling much wider tolerance to lateral offsets than any other pad. The independent nature of the windings means they can be separately tuned and regulated as required to extract power without interfering with each other. Two of the most commonly known Multi-coil designs called the DDQ and Bipolar are shown in Fig. 7. These designs can be adjusted to fit a range of profiles, but for a given sized structure) they achieve almost identical power transfer independent of whether the primary is a non-polarised circular or polarized solenoid or DD (as shown in fig 8). While the Multi-coil-DDQ is very versatile in that the central coil can be made any desired size relative to the DD coil to fit the designed transfer gaps, in the case of the Multi-coil-BP, both coils are identical but it uses much less copper, and is therefore more efficient and lower cost.

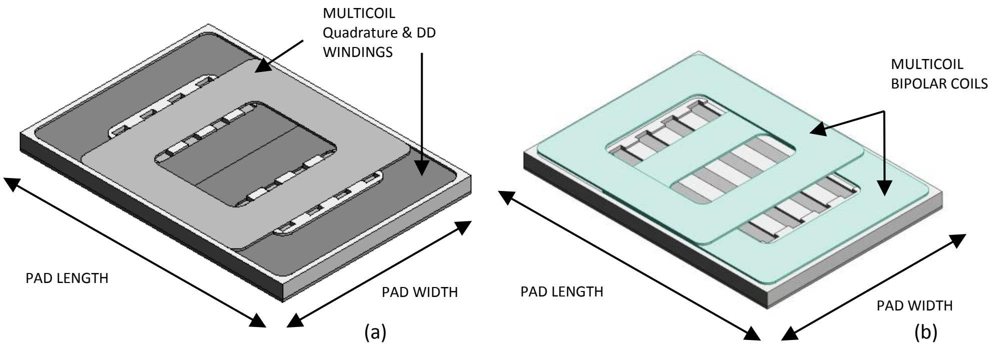


Fig. 7. Multi-coil polarized pads with independent windings DDQ and (b) Bipolar

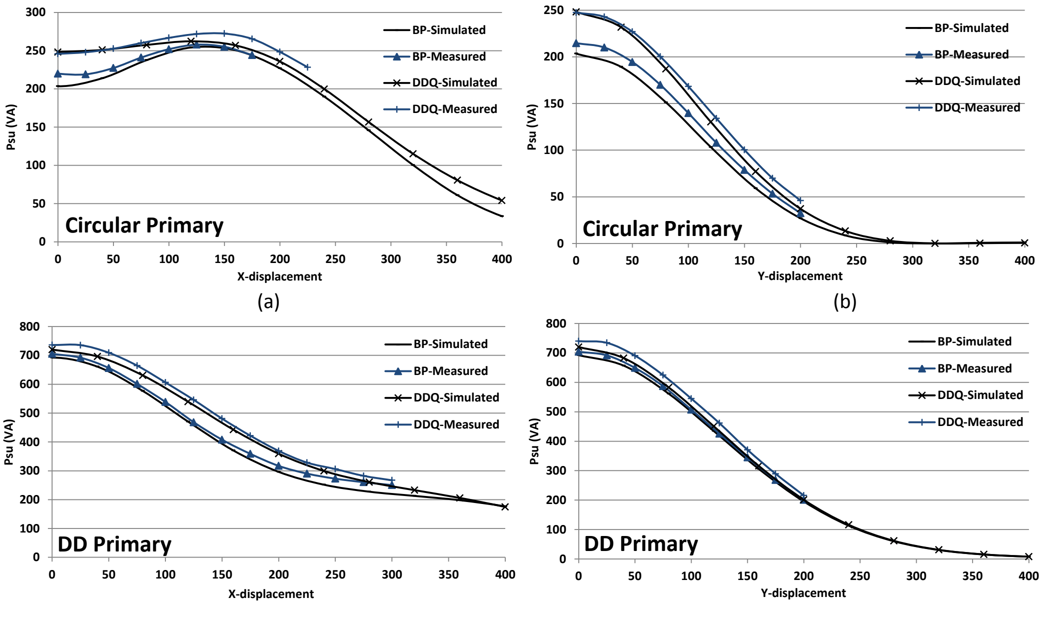


Fig.8. Measured and simulated comparisons of un-tuned output power of either a DDQ or BP secondary at 127mm gap and with lateral movement (a),(b) Circular primary and (c),(d) DD/Solenoid primary. Both primaries were energized with $\mathrm{I}_1 = 15\mathrm{A}$ at 20kHz

A further comparison of the available designs is evident in the improved coupling shown in Fig. 9.

Here the improved magnetic coupling of the multi-coil design operating off non-polarized (circular) or polarized topologies is shown (here the DD is used but a solenoid would give a similar response). As discussed later, k must be high (above 0.1 and ideally at least 0.15) to ensure low loss and high efficiency. The coupling of a single coil design falls rapidly with lateral offset. In the case of the circular pad used here which has a radius of 360mm the coupling falls off well inside the pad diameter. In comparison, the coupling of the polarized pad (with slightly smaller area but shaped in as rectangle with x:y lengths of 1.8:1) is above 0.1 in the y direction over a much larger distance, however in the x direction this coupling is similar to the circular design but falls away even more rapidly. With a multi-coil secondary the effective coupling is now the geometric mean of the couplings of the two independent coils (and can be described mathematically as k_eff= $\sqrt{\sum_{n=1}^{2} k_n^2}$). As shown the coupling in the x direction is now significantly improved irrespective of whether the primary is circular or polarized, and is well above 0.15 for all lateral offsets shown.

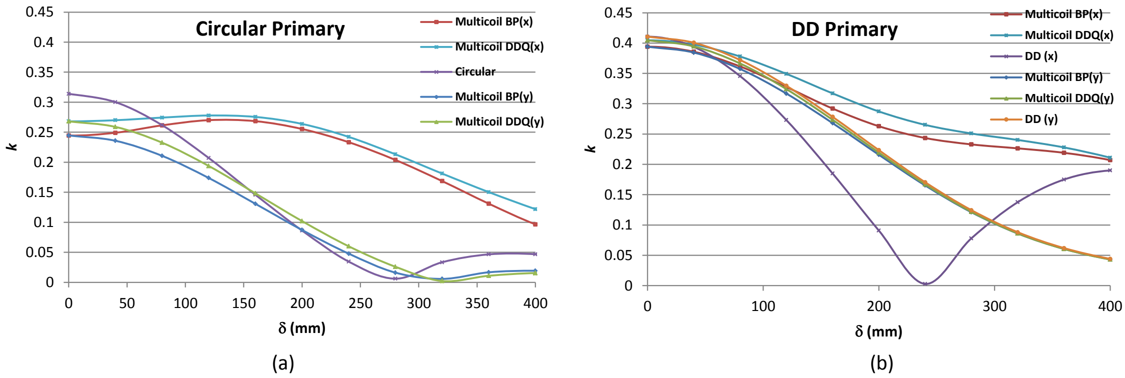


Fig. 9. Comparison of magnetic coupling factor of the multi-coil pads against circular or DD at 125mm separation with lateral tolerances in X and Y: (a) circular primary (b) DD primary

As coils are mutually independent, then they can be separately tuned and regulated as desired without impacting each other. As discussed later in section 4.3, whenever secondary side control is required (varying Q_2) regulation in the secondary is essential. One such controller option is shown in Fig. 10. Here if the coupling of a particular coil drops then it can be shut off (ensuring high efficiency) using the switches at the base of its rectifier. The regulation for the circuit Q_2 is carried out by switch S as demanded by the battery management system and the overall power control transfer strategy.

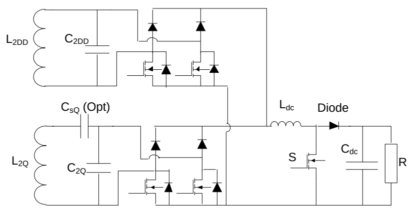


Fig. 10. One of many possible decoupling controllers for the secondary magnetics

Specific Power Comparisons between Non-Polarized and Polarized

The advantages of using a polarized primary such as the DD and secondary multi-coil structure compared with circular pads are notable in terms of the available output power. For an almost identical sized area pad compared with the material inputs. A DD primary with multi-coil secondary pad set can be 18% smaller in area compared to a matched circular system yet produce 2 x the output VA with 28% less ferrite. The system uses more wire but the power output/wire is 21% higher for a multi-coil-DDQ and around 40% higher for a multi-coil-BP. The pick-up is smaller, lighter, and easier to manufacture and is lower cost.

Power transfer zones define the physical operating region where the desired power (charge) can be delivered given a particular air gap and operational Q_2. If an operating Q_2 of 6 is assumed then this zone is generally 3 times larger if the secondary is a multi-coil pad rather than the equivalent zones created for a matched circular pad set or a matched DD pad set.

Modern Charging Pads for Hybrids and EVs

Space limitations on hybrid vehicles means that today the vehicle pad must be small due to severe space limitations.

Target Pad Sizes

Typical pad sizes presently designed to achieve a vertical Z-gap of between 80-120mm are shown in table 1. These are designed to operate with lateral parking tolerances in x or y of ±150mm without significant variation in k. Pad sizes for larger air-gaps must increase to ensure coupling factors stay high and to avoid high losses

Table 1: Typical Pad Sizes for Z gap of 80-120mm

Vehicle Pads:	Small	Medium	Large
Power	3.3 kW	6.6 kW	22 kW
Frequency	85 kHz	85 kHz	85 kHz
Target weight	5.5 kg	8.5 kg	19 kg
Pad size without mounting brackets and cable	350x215x19 mm	495x305x19 mm	650x400x25 mm

Quantifying the Power Loss for a given Pad Design

While it is possible to shrink the size of the secondary pad and provide some compensation for the consequent reduction in the magnetic coupling factor k, by increasing the VA of the ground pad, there are some natural limitations. The area of the ground pad is largely dictated by the tolerances required for parking alignment and the required gap between the primary and secondary coils. The coupling to the secondary is impacted if the secondary becomes overly small, and as the coupling factor k reduces the VA must be increased on either or both the primary (ground) or secondary (vehicle) side. In practice this increase in VA must be considered at the design time or otherwise current and voltage limits may be exceeded to achieve the desired power transfer.

The loss in any charging pad is given by:

$$P_{loss} = \frac{VA_{Pad}}{Q_{L_{Pad}}}$$

In general the secondary (vehicle) pad volt-ampere $VA_2 \approx PQ_2$ irrespective of the tuning topology, and thus the secondary pad losses are $\propto Q_2/Q_{L_2}$ for a given power output.

The primary (ground) side pad quality factor is also $Q_1 \cong VA_1/P$ if the magnetic pad losses are small relative to the output power. Under this assumption, the primary side pad losses can be determined from the power equation to be: $VA_1/Q_{L_1} = PQ_1/Q_{L_1}$, so that here again primary pad losses are also $\propto Q_1/Q_{L_1}$ for a given power output.

The highest magnetic efficiency arises if the pad losses are equal on the primary and secondary sides so that $Q_1/Q_{L_1} = Q_2/Q_{L_2}$ and under these conditions the maximum magnetic efficiency can be approximated as:

$$\zeta_{max} \cong \frac{1}{1 + \frac{2}{k\sqrt{Q_{L_1}Q_{L_2}}}}$$

Thus as shown a key factor in achieving high magnetic efficiency is to have the factor $k\sqrt{Q_{L_1}Q_{L_2}}$ as high as possible. Thus if the pad quality factors are high the system can tolerate a lower coupling and still maintain an acceptable efficiency.

For a given power output larger pads (such as the ground side) can tolerate increased losses from a thermal perspective, but the larger the VA required to compensate for a reduction in coupling, the lower the efficiency of the entire system, and the greater the chance to produce unwanted fields at the edge of the vehicle. In consequence as the power level grows and or the separation between the pads increases, magnetic topologies such as the DD, bipolar, or DDQ which naturally direct their fields vertically toward the opposing pad are highly desirable compared with a solenoidal pad which produces main flux paths both horizontally and vertically from the end pole pieces. The horizontal fields produced from the solenoidal pads are difficult to contain and if lateral tolerances are not constrained when aligning the pads, these fields can couple into a vehicle chassis, metallic objects, or cause ICNIRP limits to be exceeded outside the vehicle body.

Control Methods with Varying Magnetic Coupling (k)

There are three control methods possible to ensure power is transferred as k varies.

1. Primary side control only (only Q_1 can be varied)
2. Secondary side control only (only Q_2 can be varied)
3. Primary and secondary side control. (Both Q_1 and Q_2 can be varied)

For hybrid vehicles primary side control is desirable due to limitations in space on the secondary side. Under these conditions Q_2 is fixed for rated power transfer and cannot vary with changing k. As such the largest required values for Q_1 and Q_2 are chosen for the lowest expected k, after which with improved coupling Q_1 reduces along with losses.

Pure EV systems must couple over primary pads at varying heights due to the need to charge at home in a garage and in future above a roadside pad on street level. Here the ground side pads are likely to be buried under a waterproof bitumen layer, and therefore there is a need to have higher coupling factors than hybrid systems which may only be expected to couple in defined locations such as the home or in controlled parking buildings where pads may sit above the ground surface. If the coupling variations are likely to vary excessively in any of these cases (but particularly for the pure EV), then secondary regulation in addition to primary side control is essential to ensure the secondary Q_2 can be controlled along with the primary Q_1 to avoid excessive system loss. As shown in table 2 and discussed following, the lowest losses can only be achieved by adjusting both Q's as desired.

For dynamic applications secondary regulation is essential. But in this case the primary Q should be set based only on the expected height and coupling of the vehicle coming onto the roadway, after which secondary control of power is used.

As an example, at 85kHz typical vehicle magnetic pads have a Q_L in the range 300-500, while typical coupling factors for EV charging systems may be $k \approx 0.1 - 0.4$, depending on the relative magnetic sizes of the pads, the spacing between pads and their alignment. The tables 2 and 3 below show the potential impacts on the VA of the primary and secondary and system magnetic losses as a result of reducing k and under the assumption that the Q_L of both the primary and secondary pads is around 400.

As shown, if k=0.316 ($k^2 = 0.1$) there is a need to offset reduction in the power equation by increasing the driving VA of either the primary or secondary. If this is undertaken only in the primary, then the primary VA of either the primary or secondary has to be 10 x greater than the output power. Alternatively by design the increased VA of both the primary and secondary could be shared and increased by a factor 3.16.

If then, due to movement whether in misalignment or height variation, the coupling between the pads k reduces to 0.1 then $k^2 = 0.01$ and the combined VA output from the primary and secondary must be 100 times greater than the power output level desired.

As noted above, with primary side control only the secondary Q_2 is fixed for rated power transfer. Consequently any variation downwards in k must be compensated by an increase in the primary VA to ensure the appropriate voltages and currents are coupled into the secondary pad as expected in the design. As shown in table 2, if the operating Q_2 is too low, and k drops due to movement between the pads then the primary pad VA becomes excessive and the associated losses (in table 3) become significant causing the efficiency to drop. These magnetic losses are critically impacted by the coupling, and therefore the multi-coil pads, which keep high coupling factors with lateral tolerance (as shown earlier in Fig. 9) significantly mitigate against this effect.

Nevertheless, even with good design the total efficiency of the system will be impacted by a low coupling factor and if the operating Q is increased to produce the designed power out without thought, the magnetic losses in a single pad can grow to be anywhere between 5 and 25% depending on operation.

Table 2: Approximate impact on VA of varying k based on design and chosen operation.

Pout	k	k^2	VA_1	Q_1	Q_2	VA_2
3.3kW	0.316	0.10	33kVA	10	1	~3.3kVA
3.3kW	0.316	0.10	10KVA	3.16	3.16	~10kVA
3.3kW	0.316	0.10	3.3kVA	1	10	~33kVA
3.3kW	0.10	0.01	330KVA	100	1	~3.3KVA
3.3kW	0.10	0.01	100KVA	31.6	3.16	~10kVA
3.3kW	0.10	0.01	33KVA	10	10	~33kVA

Table 3: Approximate pad losses assuming $Q_{L_1} = Q_{L_2} = 400$, with two values of $k^2$and variations in primary and secondary operating Q

$Q_{L1,2}$	k^2	Q_1	**~ Loss in primary pad**	Q_2	**~ Loss in Secondary pad**	**Total Pad Losses**
400	0.10	10	2.5%	1	0.25%	2.8%
400	0.10	3.16	0.80%	3.16	0.80%	1.6%
400	0.10	1	0.25%	10	2.5%	2.8%
400	0.01	100	25%	1	0.25%	25%
400	0.01	31.6	7.9%	3.16	0.8%	8.7%
400	0.01	10	2.5%	10	2.5 %	5%

In practice an increase in the operating Q of either the primary or secondary pad not only increases the absolute losses (creating heat which must be removed), but also reduces the operating bandwidth of the tuned circuit, so that the system can become sensitive to variations in capacitor values which may change due to aging or thermal cycling. In consequence it is desirable to limit the operating magnetic Q's of either pad to below 10 to manage losses, and sensitivity and to retain a high system efficiency. When considering total system efficiency, from mains to battery, a further 5-8% loss is expected in the electronics.

As noted above, expected variations in Z-gap and the X and Y tolerances in alignment between the ground and vehicle pad under operation impact the magnetic design. Making any pad too small not only increases loss, but adds extra loss to the driving electronics, so that efficiency targets are challenging.

Our Roadway applications

Unlimited EV range can be realized with a dynamic charging system provided the receiver on the EV works equally well in both stationary and moving situations. Circular or other non-polarised pads such as oval or square coils are not suitable for dynamic charging as they have a null in the power profile which appears before the secondary has moved beyond the pad diameter and begun coupling to the next pad. In consequence even if non-polarised ground pads are made to touch along a highway, it is still not possible to obtain a continuous power profile even if a vehicle can be driven with perfect alignment at all times.

Multiple lines of pads offset from each other could be implemented but are not economically feasible given the gaps between pads are likely to be larger for highway systems and twice as many pads are needed.

The DD, and multi-coil pads can however produce a suitable output when laid in a row and these new couplers are suitable and would meet both stationary and dynamic requirements for roadway powered applications because the power zone is continuous in the y direction. The pads would need to be scaled in size to meet the 20-60kW required for charging and propelling a vehicle but this arrangement would make EVs more cost effective than ICEs. To illustrate the concept (and noting that larger sized DD pads are required), the pads can be buried under a road and orientated so that the width of the pad is in the direction of travel (along the y-axis). The DDs presented here are only 410 mm wide but 770 mm long and 7kW can easily be transferred when a multi-coil receiver is offset by an error of up to 205mm in the y-axis at 20kHz operation. At this point the multi-coil secondary is also effectively offset from an adjacent transmitter by 205mm in the y-axis and therefore continuous power would be provided to the EV. The power will in fact be significantly greater than 7kW here as both pads will contribute to the output so that the transmitter pads may in fact be positioned in the road with a gap between them. This will lower the cost of the system given that fewer pads are needed per km.

Using polarized pads along a Roadway

The number of pads required to populate a section of roadway is not easy to calculate as it depends on the sizes of the pads, and the tolerance to movement and misalignment. Using the assumption that the ground pad and the vehicle pad are square shaped and both the same size, and that the tolerance to misalignment is constant at 200mm then the number of pads can be calculated and a typical result is shown in Fig. 11 here for a frequency of 40kHz operation. Here the uncompensated power is shown for a given pad size and gap height. If more than 10kW is required to be transferred and the secondary $Q_2 < 6$ then as shown pad sizes of around 0.7m^2 or perhaps higher may well be needed if all roadway pads are buried by up to 100mm of bitumen and vehicle ground clearances of around 250mm exist (resulting in a total pad to pad separation of 350mm). In practice the pad sizes are normally dictated by the air-gap and vehicle tolerances, while frequency impacts the thickness of the pad and material usage.

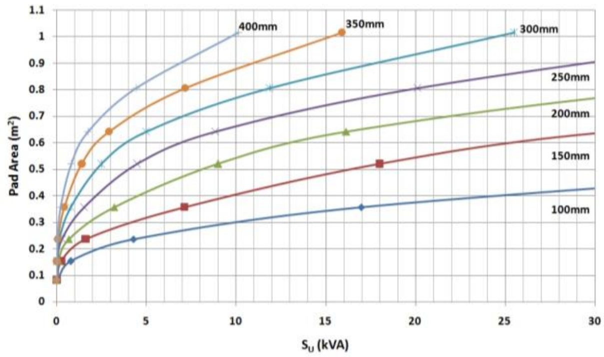


Fig. 11. Pad size versus power rating for DD pads at different air-gaps when operated at 40Hz.

Alternative Roadway Pad Systems

Alternative roadway systems have been described by Meins et al. in patent applications WO2010/000494 and 495 and by a group at KAIST. Meins uses a distributed 3-phase track with large 3-phase pick-ups for road and rail applications. The system has excellent performance but it is expensive and uses a lot of ferrite in the road. The system developed at KAIST achieves high power transfer with low emissions using a twisted two wire track buried under the road with alternating (ferrite) poles along its length. The track is narrow at only 100 mm width but power levels to 35 kW have been obtained at efficiencies up to 74% with misalignments of 240 mm (at half power and reduced efficiency). The system uses a series tuned power supply and track with parallel tuned pick-ups and achieves excellent flux leakage conditions significantly lower than ICNIRP guidelines. It uses segmented track sections 1- 60m long with a lot of ferrite in each section and is applicable to personal vehicles and public transport buses.

Both of these systems have been through more than one generation and the IPT technology has improved markedly both in performance and cost in each generation so that roadway powered electric vehicles are now more acceptable. An important feature of the multi-coil pad topologies presented here is that either can also be used to couple power from either the single phase system proposed by KAIST or a multiphase system such as that proposed by Meins, providing the tuned operating frequency of the systems are compatible. This compatibility means the new multi-coil designs are ideally suited as a vehicle pad despite the range of stationary and roadway power primary pad design options being evaluated, and this future-proofs the vehicle magnetics in a way that other proposed couplers cannot possibly do. The number of magnetic pads can also easily be increased as required under larger vehicles to ensure greater power transfer. Thus for a bus charging system, 5 x 22kW charging pads could be placed under the vehicle to enable over 100kW power transfers to be achieved.

Along with the many advances in power transfer capability, there are still many problem areas to be solved for roadway systems. These include means to reduce the cost while ensuring robust development of the roadway infrastructure where fragile magnetic materials such as ferrite have to be integrated into a concrete roadway to give a long service life electrically in a very hostile environment. Solutions to these are however being developed and will be the focus of our efforts for the next decade.

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