Modern Trends in Inductive Power Transfer for Transportation Applications

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***Abstract*— Inductive power transfer (IPT) has progressed to be a power distribution system offering significant benefits in modern automation systems and particularly so in stringent environments. Here, the same technology may be used in very dirty environments and in a clean room manufacture. This paper reviews the development of simple factory automation (FA) IPT systems for both today's complex applications and onward to a much more challenging application—IPT roadway. The underpinning of all IPT technology is two strongly coupled coils operating at resonance to transfer power efficiently. Over time the air-gap, efficiency, coupling factor, and power transfer capability have significantly improved. New magnetic concepts are introduced to allow misalignment, enabling IPT systems to migrate from overhead monorails to the floor. However, the demands of IPT roadway bring about significant challenges. Here, compared with the best FA practice, air-gaps need to be 100 times larger, power levels greater than ten times, system losses ten times lower to meet efficiency requirements, and systems from different manufacturers must be interoperable over the full range of operation. This paper describes how roadway challenges are being met and outlines the problems that still exist and the solutions designers are finding to them.**

***Index Terms*— Inductive power transfer (IPT), roadway powered electric vehicles, strongly coupled magnetic resonance, wireless charging systems.**

I. Introduction

INDUCTIVE power transfer (IPT) was first suggested soon after Ampere and Faraday proposed their laws that became the underpinning of electrical engineering. Following this, the most significant advances were made by Tesla who demonstrated significant power transfers at ac frequencies using highly resonant tuned coils [1], [2]. The means by which such power, however, could be transferred at low cost, and regulated, remained a challenge which was difficult to overcome with the technology of the day. Therefore, IPT was considered to be not viable for some time and against a background of disbelief it was not until the end of the twentieth century that real commercial IPT systems appeared [3]. IPT involves the coupling of two or more coils: when coupled a current in one coil causes an induced voltage in the other hence under the correct conditions that voltage can be used to power some application and in these circumstances power is transferred by induction from one coil to another without physical contact. Such power transfer is clean, unaffected by chemicals or dirt, and has the capacity to revolutionize many manufacturing processes.

Early commercial IPT systems found applications in car assembly plants where tolerance to paint and welding fumes was highly prized [4]–[8] and also in transcutaneous medical devices [3]. In manufacturing applications, one primary circuit was able to drive a multitude of secondary circuits using new decoupling controllers that could switch a secondary pickup circuit on and off without placing a VAR load on the primary circuit [7]. IPT systems, however, really found their application with clean factory automation (CFA) manufacturing flat panel displays and computer chips under stringently clean conditions and achieving higher yields than any competing technology [3]. The technology has continued to evolve to include larger more powerful systems, operating under difficult conditions in worldwide applications.

Perhaps the biggest challenge for IPT systems today is transportation for both public and private vehicles on networks of railways and roadways in every country in the world. IPT offers the possibility of being able to power these vehicles electrically using electric wires under the ground to provide power, charge, and alignment means [9]–[45] for cars, buses, and trains by magnetically coupling power directly into a pad placed underneath a vehicle. If power transfer is accomplished with a stationary vehicle and a battery, it is called wireless charging of a battery electric vehicle (BEV), and developments here have accelerated over the past decade [9]–[34]; if it is accomplished while moving it is called dynamic powering, and while concepts were developed in the early 70s [35], [56], [79], only recently has this begun to receive renewed attention due in part to stationary charging developments and a willingness of car manufacturers to support this technology [36]–[45]. BEVs are now challenging internal combustion engine (ICE) vehicles in all applications of vehicles in our society except range; dynamically charged electric vehicle (EV) will compete with ICE vehicles in all aspects of performance except original purchase cost: they are cleaner, quieter, and more efficient and with the appropriate roadway structure they could have unlimited range [40]. BEVs can operate with a plug in battery charger or with inductive charging: dynamically powered vehicles can only operate with an IPT link and it is the development of that link that holds the promise for EVs in the future.

IPT is a technology of the time, totally dependent on recent developments in magnetic materials: litz wire, embedded controllers, and particularly power electronics. Over the past 30 years the operating frequency for power transfers

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$\sim$1–10 kW has increased from typically 10–20 kHz over small (relatively confined) air-gaps but now there is a push to 85 kHz and beyond at significantly larger spacing between the resonant couplers. The power rating has also continually increased from 3 to 100 kW and higher as more applications are developed. Lower power IPT systems used for charging cell phones, medical equipment, and other small IT devices are developed over a similar time period, initially in the 100–400-kHz region to keep the magnetic systems small without being overly concerned with efficiency, but more recently operation $\sim$1–10 MHz has been developed and higher frequencies are being proposed but again are restricted to very lower power applications ideal for harvesting power [2]. The names for such IPT systems vary, and include contactless power system (CPS), wireless power transfer (WPT), wireless energy transfer, strongly coupled magnetic resonance, high-efficiency inductive-power distribution and others; however, the essential principles are the same given the distances over which the power is coupled is almost always within one quarter of a wavelength and therefore, the fundamental operation of all of these systems can be described by simple coupled models.

This paper reviews the essential elements required to develop high-power IPT systems and comments on the key metrics which must be considered, including safety, field leakage, and heating. It also describes its latest challenge—as a key enabler for EVs to increase the range and eliminate the need to plug in.

II. Power in IPT Systems

In its simplest form an IPT system comprises two coils L_1 and L_2 with mutual inductance, M. For a current I_1 in L_1 at frequency ω, the voltage induced in L_2 is $V_{\text{oc}} = j\omega M I_1$ and is commonly referred to as the open-circuit voltage of the coupled system. If the secondary (pickup) is short-circuited the short circuit current is $I_{\text{sc}} = V_{\text{oc}}/j\omega L_2 = M/L_2 \cdot I_1$. From first principles, the product of the short circuit current I_{sc} multiplied by the open circuit voltage V_{oc} is the maximum VA rating for the pickup called P_{su} and gives a measure of how good the power coupling of any magnetic system is for a particular driving condition. The maximum power that the system can transfer—called here P_{out} is [7] as follows:

$$P_{\text{out}} = P_{\text{su}} \times Q_2 = \omega \frac{M^2}{L_2} I_1^2 Q_2 \tag{1}$$

where the factor Q_2 is the loaded Q of a secondary system that is compensated with a tuning capacitor hence it operates at resonance, as used by Tesla. This power equation is valid for all manner of IPT systems but some minor adjustments may occur in track-based systems driven from a current source when the inductance L_1 can be very large. Pickups in track systems are usually in a close relationship with the track and can partially enclose the track inductor giving high k values (where $k = M/\sqrt{L_1 L_2}$ is the magnetic coupling factor) that are not achievable with floor-mounted systems such as AGVs or moving robots. Nonetheless regardless of the value of k the analysis can proceed in the same way.

Following (1), the power transferred by an IPT system can be improved by increasing any of ω, M, I_1, or Q_2. There are, however, advantages and disadvantages with all of these possibilities. Increasing the power by increasing the frequency is something of an illusion and may not bring about the benefits expected. The system is clearly frequency sensitive but it is not a simple dependency as it appears here and this limit is described in the next section. Increasing the mutual coupling is without doubt the best solution as it involves making the magnetics better and as this is a magnetic coupling it is really the ideal approach, but there are limits in terms of magnetic coupler size and volume of material that must be considered for each application. Increasing the excitation current is a forced solution that usually leads to a lower efficiency. It will give more power, but it puts more stress on all the components in the process. Increasing Q_2 of the secondary electrical circuit is a good solution but as described below this increases the VA of the secondary and narrows its bandwidth (much in the same sense as tuning a radio receiver). It cannot be carried to excess or the system becomes too difficult to tune and keep on tune over time (because of aging effects of capacitors) or in uncontrolled environments (where the presence of materials or movement can shift the inductance value). These possibilities are examined in the next section.

A. Power from the Viewpoint of Electrical and Magnetic Quality Factors

For systems where there is normally one primary and one secondary as in charging applications, (1) may be rewritten as follows:

$$P_{\text{out}} = \omega L_1 I_1 \times I_1 \times \frac{M^2}{L_1 L_2} \times Q_2 = V_1 I_1 \times k^2 \times Q_2. \tag{2}$$

In this form, the power transfer can be seen as the input VA, multiplied by the magnetic coupling factor k^2, multiplied by the electrical quality factor of the loaded secondary circuit Q_2, and is not dependent on ω that is now included in the voltage at the input of L_1. In other words, the transferred power can be increased by increasing the NI product or primary frequency until the VA limits of the primary system are reached, after which additional compensation may be required (which would then add to the system cost). If the power demand is fixed, and this limit is not reached, then an increase in frequency at the same voltage lowers the B field in the air-gap and in any ferrite which may be present, and enables a smaller volume of copper to be used.

The size of the magnetics in a charging application using pads is largely determined by their expected tolerance to misalignment. For a misalignment of 200 mm, at least one of the pads has to be circa 400 mm across hence under misaligned conditions an overlap exists whereby energy can be transferred. A given pad needs essentially the same input VA for a given power regardless of the frequency. For a given power and VA rating, increasing the frequency requires a reduction in pad inductance by partitioning the wire into segments and adding series compensation to manage the voltage. Simply reducing N makes the windings sparse and the leakage flux may increase. The area of ferrite may also be reduced but it must contain the flux. It can be made thinner but then it is more likely to break. A good practical reduction is to reduce the NI product by two with a bifilar winding—but the power supply must now deliver twice the current. The efficiency of the power electronic supplies and secondary electronics operating at LF frequencies is usually very high. Power supply efficiencies are typically ∼95% while the secondary electronics and control can have an efficiency as high as 96%–97% when it is operating under ideal conditions. Normally forced cooling is not required. There is a natural desire to be able to couple power at an efficiency of ≈90%, and therefore the couplers also need to have efficiencies ∼96%–97%. For this reason, most couplers use ferrite and litz wire, to shape the field and ensure the conduction losses are low. The designs of such couplers have evolved with the applications, but from the very first commercial systems in the ’80s there was a clear understanding that all couplers must be low loss.

The loss in any tuned coil is the VA in the coil divided by its native Q [30] and therefore, all commercial systems use resonant coupling coils with high native Q (for the inductor this is labeled here as $Q_L = \omega L/r_{ac}$, where r_{ac} is the intrinsic resistance of the wire in the coil inductor at the operating frequency).

Thus, the magnetic loss in either the primary or secondary at a given power transfer rate can each be defined as follows:

$$P_{\text{loss}} = \frac{VA}{Q_L}. \tag{3}$$

The VA of the secondary is [46], $P_{\text{out}}\sqrt{Q_2^2+1}$ for a parallel resonant secondary, or $P_{\text{out}}\ Q_2$ for a series resonant secondary system, and as most systems operate at rated power with nominal loaded $Q_2 > 3$ both approximate $P_{\text{out}}Q_2$. Thus, the magnetic power losses near rated power transfer are as follows:

$$P_{\text{loss}} = \frac{VA_1}{Q_{L_1}} + \frac{VA_2}{Q_{L_2}} \approx P_{\text{out}}Q_2\left(\frac{1/(kQ_2)^2}{Q_{L_1}} + \frac{1}{Q_{L_2}}\right). \tag{4}$$

IPT systems are normally designed to operate such that the effective VA in the primary is usually greater than the VA of the secondary (or combined secondaries) [7], [47], but care must be taken when these VAs are closely matched if the system operates under variable frequency conditions—given this is nominally the point at which bifurcation can occur and power drops. In fixed frequency systems operation close to this point is essentially the best operating condition and usually guarantees good efficiency. In a charging system, similar sized couplers (which usually have similar VA limits) are normally designed to operate with maximum VA while delivering rated power at the largest lateral displacement and clearance. Therefore, at this point $kQ_2 \approx 1$, hence the magnetic losses of both the primary and secondary at rated power, are proportional to Q_2/Q_L. With more displacement there is a need to reduce the power delivered or risk operating beyond the pad ratings and shortening their lifespans.

If the ideal magnetic losses are desired to be 2%, then in a matched coil system operating at the point where both are close to rated VA, each system should operate with ≈1% loss. This equates to a desire to operate such that $Q_L/Q_2 > 100$. As an example of a typical commercial design, Wang *et al.* described a 20-kW system where the primary track had a $Q_{L_1} = 148$ [48], similarly Hu described a 400-m track system and pickup operating at 15 kHz, where $Q_{L_1} = 195$, and $Q_{L_2} = 565$ [49]. In this application, each pickup is designed to deliver 10 kW of power to a light rail train under development in Germany by Conductix–Wampfler AG and is expected to operate with a loaded Q_2 of ∼4. Thus, the magnetic losses or each secondary is ∼1%. Similar examples of designs by Vahle in 2001 for their CPS system in Dresden which has been operating since 2001 have measured $Q_L > 200$ [50] while de-Boeij *et al.* [51] also showed built coupler systems with $Q_{L_1} = 308.6$, and $Q_{L_2} = 314$ in the primary and secondary, respectively.

Thus, high-Q coils are essential to guarantee low loss but the terminology in the literature was rather confusing and seemed to imply a difference between the recently presented research by Kurs *et al.*, [52] which they labeled as strongly coupled magnetic resonance, and commercial resonant inductive systems even as early as those described above. In [52] and [53] there are two coupled resonators with intrinsic loss rates Γ_1 and Γ_2 that are coupled together at a coupling rate K. The resonance quality factor for each resonator is $Q_L = \omega/2\Gamma$. The WPT figure of merit is $U = K/\sqrt{\Gamma_1\Gamma_2}$. In conventional electrical engineering terminology, the same statement may be written as: there are two tuned coupled circuits with a coupling factor k and a WPT figure of merit $U = k\sqrt{Q_{L_1}Q_{L_2}}$ where k, Q_{L_1}, and Q_{L_2} are all defined earlier. As discussed, the quality factor of each coil that is $Q_L = \omega/BW$ (where BW is the bandwidth of the tuned circuit), can also be related to the damping factor of each circuit, or to the electrical parameters of the circuit described earlier.

This nomenclature in [53] is generalized for any type of resonator, whereas the electrical one only applies to electrical resonances—which in practice comprise the overwhelming majority of all resonators. Expressing the figure of merit in two forms $U = 2K/\omega_o\sqrt{Q_{L_1}Q_{L_2}} = k\sqrt{Q_{L_1}Q_{L_2}}$ shows that the unloaded Qs of the two circuit couplers is the important factor—and always has been. Here, $\omega_o = \sqrt{\omega_1\omega_2}$ is the operational frequency of the system, and is the geometrical average frequency of the individual coil resonant frequencies $\omega_{1,2}$ of coils one and two, respectively. As defined in [53], a system with $U > 1$ is strongly coupled. As such the majority of all practical IPT systems operating under resonance are strongly coupled since as shown earlier $\sqrt{Q_{L_1}Q_{L_2}} > 100$ is common requiring $k > 0.01$ which is true of nearly all systems, and for charging systems most have $k > 0.1$ under all desirable power transfer conditions.

B. Power from the Viewpoint of Energy Storage

The power equation may also be written as follows:

$$P_{\text{out}} = \omega \times L_1 I_1^2 \times \frac{M^2}{L_1 L_2} \times Q_2 \tag{5}$$

where the power is seen to be 2π times the frequency multiplied by the product of the peak energy stored in the L_1 inductor, the square of the magnetic coupling factor, and the loaded Q of L_2.

Further, as the energy in the inductor is essentially stored in the air-gap of a practical IPT system, the peak energy stored

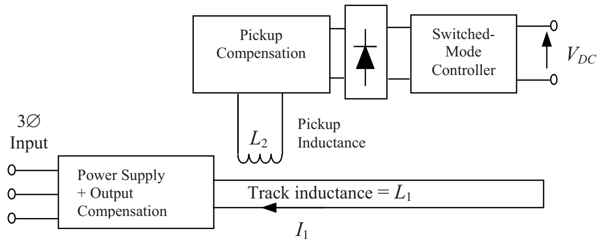

Fig. 1. Typical IPT system.

may be written as: Peak Energy $= B^2/2\mu_0 \times$ the volume of the air-gap separating L_1 and L_2. Here, B is the rms flux density. Thus, simplistically the maximum power that can be transferred by an IPT system includes the frequency, the flux density, the coupling factor, and the size (volume) of the air-gap. This analysis has not included the flux caused by the secondary coil and its loaded Q but it does show that in general higher powers will require higher flux densities.

For charging systems there is always a desire to reduce the size of the secondary system (e.g., in cell phones, robots, and EVs), and thus at any given frequency and power transfer, this necessarily increases the B in the gap given the coupling between the primary and secondary will reduce with size. Therefore, both the primary and secondary will have to be driven harder to compensate for this reduction, thereby lowering the system efficiency. If the primary is larger than the secondary (and this is often desired to increase the tolerance of the system to misalignment), then there is an even greater chance of creating leakage if the smaller secondary cannot capture the field. In all of these cases, the potential levels of flux, where humans will interact with these fields, must be considered and maintained within ICNIRP limits [54], [55], while also ensuring that objects in the gap are not heated in a manner that creates a safety hazard.

III. Elements of an IPT System

A simple IPT system is shown in Fig. 1. It comprises of the following:

1) a power supply that takes electric power from a utility or a battery;
2) an elongate track that is driven by the power supply whereby current in the track causes a magnetic field that follows the track;
3) pickups on or along the track that intercept some of the magnetic field and convert that intercepted field to controlled electricity;
4) electrical loads that may be driven by that electricity.

All of these aspects are important but some are essentially self-evident. There are a very large number of power supply circuits that may be used in an IPT system but all of them achieve the same outputs with different output frequency, efficiency, and reliability, however, modern IPT supplies generally favor current controlled supplies with unity power factor and with a controlled frequency [3]. The frequency must be system wide but other attributes will vary with cost and availability. The track usually uses high-frequency litz wire to support the magnetic field. The wire, current, frequency, and wire to wire spacing are all gradually becoming subject to international standards—in FA 80/125-A wires spaced 100-mm apart operating at a frequency of ~20 kHz are an industry standard. Pickups (magnetic couplers) may run on the floor, or on monorails controlled by signals superposed on the wires or separately transmitted [4]–[8].

In other aspects, there may be considerable freedom in the design of IPT systems especially in the pickup circuitry, its protection, the controllers, and the electrical circuitry and Q_2. The most flexible characteristic of all is, however, probably the magnetic circuits and how they are coupled. Such IPT systems are loosely coupled with k values that may be as low as 0.01 or as high as 0.3–0.5 or more in some circumstances. But the difference between a system with a k value of 0.01 compared with an alternative system with a k value of 0.03 is a factor of nine: this can be compensated by increasing Q_2 by nine times but then the system becomes less efficient and difficult to tune as the coupler alignments and the ambient temperature vary. To this end, a significant effort in the design of IPT systems is to increase k by improving the magnetic designs. Simple coils wound about a ferrite core have flux out both sides of the coupler—the flux out the obverse face can never couple to the other coupler therefore, new coupler topologies are developed where there is no reverse flux. Flux paths are shaped by attractors (ferrite) and frighteners (aluminum or copper). Combinations of ferrite and copper can greatly improve the flux path geometry giving significant increases in k while also reducing other leakage paths.

IV. Magnetic Components in IPT Systems

IPT systems use two or more magnetic couplers to transfer power from one frame of reference to another. As noted above, in the discussion on the power equation, arguably the most important factor in an IPT system is the magnetic coupling coefficient k and techniques that increase k lead directly to systems that can transfer power more efficiently than others. There may, however, be a cost penalty as magnetic materials such as ferrite are expensive and fragile and in circumstances where a large lateral tolerance to misalignment is needed the cost may be excessive. Where low powers are involved the magnetic material may be omitted and pickups may be coupled magnetically through the air. The required Q_2 may be higher and the efficiency lower but the system is justified by its cost.

From the earliest systems there is always a balance, such as this, to meet some figure of performance. Otto [56] in 1973, for example proposed a system for powering an EV with an air-cored pickup coil >300-mm above the surface of a road using a primary of two copper tubes buried in the road, each with a current of 2000 A at 10 kHz. The system was never built but avoided the use of ferrite as it would have been prohibitively expensive. Today, that solution would be unacceptable in that emissions from it would be too high—but from that time different solutions to the power transfer problem have continued to be innovative in a wide variety of applications. In the early 1990s, a monorail conveyor for FA used IPT at 10 kHz with a track current of 80 A using two wires at a spacing of 100-mm mounted close to an aluminum I beam that was the backbone of the monorail [7]. Here, the primary is essentially in air (near the web of the I beam) and the secondaries used ferrite E cores with a litz wire winding to each collect $\sim$1.5 kW from the primary as they moved. This is an efficient system using a different magnetic structure at each end of the coupling and was unique in that it included a control system that allowed individual conveyors to be regulated without compromising other conveyors on the same track.

A modification to this used the same controller but the two wires are horizontally displaced in air with currents of 80 A each, at a frequency of 10 kHz and pickups made of ferrite in a horizontal H shape picked up power using a litz wire coil on the cross bar of the H. This system allowed one of the power wires to be switched hence a carrier could go from one track to another at half rated but continuous power and it soon became an essential element of IPT conveyor systems in CFA systems. In FA, IPT systems are chosen for their tolerance of dirt in welding bays and paint shops; in CFA situations IPT systems are chosen for their cleanliness and residue-free applications.

Pickups in these and other factory applications were widely named according to the letter of the Latin alphabet that they most closely resembled—for example I, E, and H—but other shapes were also suggested—for example an asymmetrical S pickup is difficult to mount but gives almost twice the available power as a symmetrical E pickup for the same material cost [57]. A feature of all of these pickups was that they operated with relatively small air-gaps, and good coupling factors at high efficiency. As the technology and its applications developed these ideal operating conditions, however, became more stressed. Floor-mounted systems used two wires 100-mm apart buried under 10 mm of concrete, each with a current of 125 A at 20 kHz. In their primitive form they used a flat E pickup to achieve coupling factors within 50% of those attainable with a monorail. In monorail applications, the tines on the E and H pickups could encircle the track to $\sim 270°$. Floor-mounted pickups could not encircle even to 180° giving a low output but they could sense the wire position under the concrete floor and use this information to navigate around the factory. Also, in a new innovation, extra coils could be added to the flat E ferrite converting it into a quadrature pickup where both the power profile and the tolerance to misalignment are enormously improved [58], [59]: in the primitive flat-E pickup power at typically 1 kW was available over a misalignment of $\pm$25 mm with an air-gap of 10 mm; in the improved pickup operating with the same track current, this same power was available over $\pm$150 mm.

The floor-mounted pickups do, however, have the whole track energized all the time and as this may be as long as 300 m it does create a large area in the factory closed to personnel. Overhead monorails have a track 3.4-m high and this makes them inherently safe—but not usable for EVs.

In construction, couplers are fragile and means must be found to protect the coils from damage. The protection usually entails packaging the coils in soft plastics or rubber materials that add significantly to the bulk of the pickup without adding to its function. The situation is particularly critical as with the high relative permeability of the ferrite in the order of 2000, a crack 10 microns wide is equivalent to 20 mm of ferrite.

V. Charging EVs Wirelessly

In the push to obtain EVs powered by IPT this background in FA technology is useful but inadequate. With FA, the misalignments and the air-gaps are small but in the EV application they can be large. Present systems would run happily at 2–3 kW/carrier, and occasionally higher, but with the EV much higher powers are needed. For stationary charging, a power level of at least 7 kW is needed while in dynamic applications 20 kW is fast becoming the design specification. The biggest difficulty of all is that unlike FA, people are, however, commonly near to EV charging equipment and the emissions from the vehicle must be contained below international standards. On the roadway with a moving vehicle, this may not be a problem but in a garage situation it is important that the magnetic field outside the footprint of the car does not exceed field leakage limits [54], [55].

Traditionally, practical couplers for EV systems are either circular in shape with a coil in the form of a flat Archimedean spiral placed on magnetic material or shaped like a solenoid using a cylindrical spiral with a magnetic material through the middle of the coil. Such systems have evolved from essentially track-based designs to concentrated couplers. One of the earliest systems was the Santa Barbara project [60]. Here, the proposal focused on designs that used a track system as is commonly used in materials handling even today. An extended loop is built and a large flat E-core pickup designed and fitted under buses and also under cars (in the playa vista project work). The essential problem that limited this application was the unavailability of modern materials. Without ferrite and litz wire, the pickups are too heavy and without modern power electronics the frequencies are too low (in the early work $\sim$400 Hz) rather than 20 kHz or higher. The power control means was, however, also lacking. In consequence, while the concepts and designs were well thought out, the tolerance for parking or moving is highly constrained, and the cost was too high.

In the early mid-90s, plug-in inductive couplers were proposed [61]–[66], but while adding a level of safety they did not solve the fundamental issue of having to remember to plug in. In the late 90s and early 2000s there was significant redevelopment and limited deployment of plug-less charging systems. Both solenoidal and circular or oval-shaped systems were reinvestigated and deployed successfully with high-efficiency and high-power transfers of between 20 and 60 kW, but tolerance to movement was constrained to gaps of between 2 and 4 in [14], [67], and [68]. The focus then shifted to improving the distances over which power could be coupled efficiently without oversizing the magnetics.

A. Large Air-Gap Circular Magnetic Systems

Mecke *et al.* showed, based on research undertaken and published over the preceding 4 years, that suitable power transfers for charging EVs could be achieved at high-efficiency over large air-gaps [13]. In this paper, they recognized that very large air-gaps of several hundred millimeters were going to be essential at high efficiency, and therefore investigated the use of highly resonant coils constructed using litz wire on top of a ferrite plate, carefully tuned to operate at different transmission frequencies between 20 and 150 kHz to determine the best and most efficient operating point. They also investigated how to size the magnetic system for such large air-gaps. Here, they investigated power transfers over air-gaps of up to twice the coil diameter. Their built system, was driven from a series tuned resonant converter and operated at 100 kHz to transfer 1 kW over an air-gap of 300 mm using matched circular couplers each having a coil diameter of 400 mm. The complete system achieved an overall efficiency $>80\%$ including all the power electronics. This system represented the state-of-art of such systems at that time, but it did not consider the impact of tolerance to misalignment, and neither did it consider flux leakage. As constructed with the coil at the outside of the ferrite, this pad was essentially a mono-pole resulting in fields which radiate out from the center of the pad and are not easily returned and therefore, create significant leakage that must be contained [69].

Similar development research was also being undertaken at Sojo Universities [70], and the University of Auckland [26] around this period to optimize the design of the ferrite couplers, and this culminated in various systems discussed and displayed in the late 2000s at high efficiency and with good tolerance. The system that most closely resembled Mecke's was displayed at EVS 2009 in Stavanger and is discussed in [26]. While this Auckland system operated at a modest 20 kHz, 2 kW of power was able to be transferred over clearances of 220 mm while also allowing lateral tolerances of up to ±150 mm. The efficiency of the entire system was over 85% (including all the power electronics) and required no forced cooling as the magnetic coil loss is only 2%–3% in each coil spread over a relatively large area and convection cooling was sufficient for the power electronics. In this paper, a larger circular pad structure was deliberately constructed and had a flat Archimedean coil covering $\sim25\%$ of the pad's radius (from 45% to 70%) to give the best power profile. The average coil diameter was also ~400 mm but required a total pad size of 700-mm diameter as shown in the photograph of Fig. 2(a). The larger pad size resulted from a desire to reduce field leakage around the pad that had become essential because of ICNIRP guidelines [54], [55]. This field reduction was achieved by extending the ferrite out beyond the coil to essentially capture the returning main flux, and also included an aluminum ring to help shape the flux and direct it toward the opposing pad [26], [33] to create an essentially single-sided field. For stationary charging applications of vehicles with circular pads, the vehicle must be parked such that the pads are in close alignment as if the misalignment gets offset by around $\pm40\%$ of the pad diameter (which is the limit of the coil), the coupled power falls to zero. The advantages of these circular pads are that the vehicle can approach them from any direction, and the emissions are relatively low for a given power transfer providing as suggested, the ferrite is extended beyond the coil. Even so, compared with the power and size demands from the automotive industry, the power output from

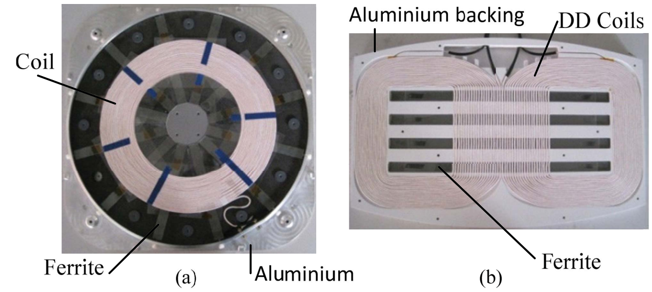

Fig. 2. Typical single-sided magnetic coupler designs. (a) Circular and (b) polarized DD.

two such circular coils with a large air-gap is quite low and the tolerance to misalignment is not as good as desired.

In 2005, there was considerable interest in research presented by Kurs *et al.* [52] and specifically in using circular coils to couple over very large air-gaps similar to that described by Tesla [1], [2]. Of particular interest was the ability to transfer useful power with clearances of up to 3 m using frequencies $\sim$4–6 MHz; however, this was achieved using self-resonant open coils with no shielding and therefore concerns as to how much power can be transferred taking into consideration ICNIRP regulations remain. As discussed earlier—to remain efficient it is desirable to have $Q_L/Q_2 > 50-100$ under operation, hence if at these higher frequencies $Q_L > 1000$ then it is possible to have a $Q_2 \approx 10-20$ or even higher if efficiency is not such a problem. To couple over even larger distances still, resonant repeaters can be used, as originally proposed for both electric buses and lighting systems [71], [72] but given these repeater coils cannot be placed in the gap, the additional cost and bulk of these coils may not justify the increase in power.

Nevertheless, a great deal of investigation has continued in this area to exploit potential applications [2], however, when commercializing inductive power technology for vehicle charging the recent focus is on frequencies of between 20 and 150 kHz depending on the power level. For private vehicles frequencies $\sim$50–100 kHz are likely because of the attempt to find a practical balance between high efficiency and low cost, against low volume of material and low leakage. There are a number of significant issues that need to be addressed if the frequency is pushed higher, including finding low-cost capacitors and suitable coil constructions [73] that can operate in the megahertz region to carry the necessary currents at high efficiency, as discussed by [2]. For applications at lower power that can tolerate lower efficiency these frequencies appear promising to enable smaller magnetics with low leakage.

B. Polarized Solenoidal Magnetic Systems

With conventional coupled systems, the poor coupling ability of circular pads is largely because significant flux paths cannot have a footprint beyond the coil, which in the circular pads with low leakage is $\sim50\%$ of the pad diameter. Thus, to a first approximation, the highest flux paths are lower than the overall pad diameter divided by four [41]. With different pad structures, called polarized pads, the flux height, however, can be significantly higher at the expense of limiting access.

Thus, for example, a polarized pad can only be approached in one direction, whereas as noted a circular pad can be approached from any direction but for the polarized pad, the gain in flux height is essentially a factor of two times higher than for a circular coil with the same linear dimension, corresponding to coupling factor k that may be 20%–25% higher. The first polarized coils used essentially a flat ferrite plate with a solenoidal coil wound on it to produce high arching fluxes out both sides of the pad [60], [67], [74]. Only one of these is required therefore the other is suppressed by covering that half of the winding with aluminum or copper. In this form, the extra copper/aluminum losses may reduce the native Q of the coil to significantly <100 and make a relatively high-loss pickup coupling system. Improvements to such a system were suggested [28], [29] but as shown expected magnetic losses can be as high as 10% when ideally not more than 2%–4% is desirable. These coils also produce a strong horizontal flux out the ends of the pad and this is particularly difficult to suppress to limit field leakage concerns. In some system designs, adequate suppression is achieved with H shaped ferrite structures [28]–[30] by raising the frequency of operation to near 100 kHz, and rotating the ground coil through 90° hence the unwanted flux is north/south in the car and as cars are longer in that direction there are more possibilities to reduce the flux.

C. Single-Sided Couplers: Circular Versus Polarized

Single-sided polarized coils such as the double-D (DD) [31] have developed from the solenoidal coil in an attempt to further improve the unloaded coil Q. Here, a flat planar bed of striated ferrite is used in place of the solid ferrite plate in the solenoidal coil as shown in the photograph of Fig. 2(b). The striated ferrite enables a weight reduction and changes the reluctance hence the plate is more permeable along the ferrite and less permeable across it. The DD pad uses two flat Archimedean circular spiral coils made of litz wire, lying flat on the striated ferrite and touching along a common line that is at right angles to the striated ferrite direction. These two coils may be wound with one piece of wire. The line of contact is extended by loosening the windings near to it. This forms a structure where two spiral coils merge into a flux-pipe between them. The winding sense of the coils is such that if one is instantaneously a north pole the other is a south pole hence a typical flux path travels through the ferrite to a pole piece at the center of one of the spiral coils, it arches high through air to the other pole piece, and returns to the starting point through the ferrite.

Like the circular pad of Fig. 2(a), this DD pad in Fig. 2(b) only produces flux out the coil side of the ferrite—there is no flux out the back, and minimal flux out the ends of the ferrite. It requires no aluminum to screen it but may use aluminum behind the ferrite for structural integrity. Typically, the pickup coil will have a $Q_L > 350$ [31]. The outputs of a matched pair of circular and DD couplers having almost identical areas and inductances were compared under identical driving conditions (V_1 and I_1 are the same at 20 kHz) [31], and as shown in Fig. 3, the DD system has a much wider coverage in both the x- and y-directions and launches flux so high in the z-direction

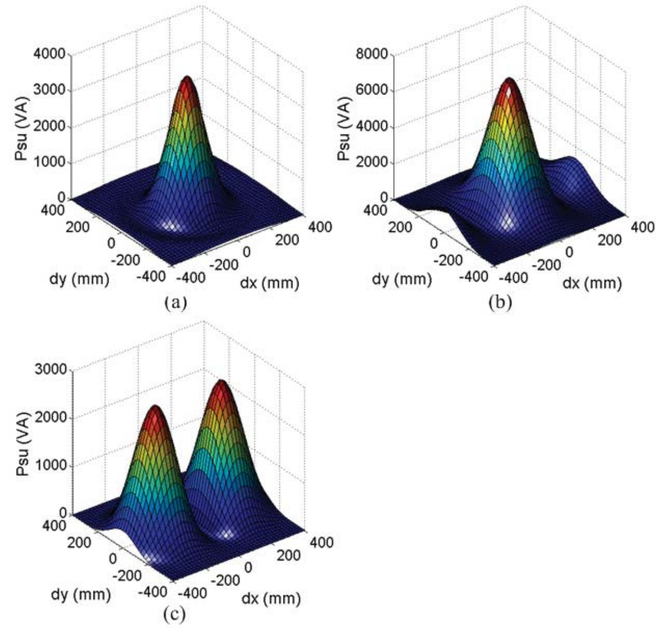

Fig. 3. Untuned output power of various single-sided topologies with lateral movement at a clearance of 125 mm with $I_1 = 23A$ at 20 kHz. (a) Circular on circular. (b) DD on DD. (c) DD on circular.

that it is ideal for stationary charging given that smaller sized couplers could potentially be used for the same power transfer if required. In addition, as discussed later in Section VI, it is also ideal for dynamic powering in roadway applications.

Of particular importance is the need to keep the system on the car as small as possible, and given polarized systems have excellent coupling capability, one possibility is to have a circular primary that is slightly larger, and a smaller polarized secondary, which would bring together the benefits of both systems. As shown in [33] and in Fig. 3(c) for the designs with identical areas, such a polarized and circular system can be interoperable, but there are now two regions where power can be usefully coupled but not where they are perfectly aligned. An issue of concern, however, is the potential flux leakage and heating effects that could result because of the need for such an offset in operation.

D. Single-Sided Multicoil Polarized Couplers

New magnetic structures have also derived from the DD coil topology to enhance the interoperability of the magnetic design either as a primary or as a secondary system (or both) [31]–[34]. These topologies enable almost all of the features of both the circular and simple polarized magnetic designs to be included but with useful improvements. Because of their coil structures that are designed to be magnetically independent (although existing within the same ferrite structure), they can capture and use almost all of the flux present providing they are oriented correctly (as for polarized systems). Conceptually, they capture both the sine and cosine of the flux vector and are therefore quadrature systems as described following. They can be used for both stationary charging and for dynamic applications and they can also be used in both single-phase and three-phase applications without compromise. They are tolerant to misalignment and to significant variations in the air-

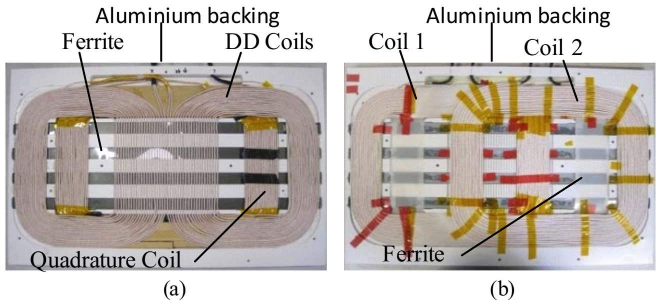

Fig. 4. Multicoil single-sided magnetic coupler designs. (a) DDQ. (b) BP.

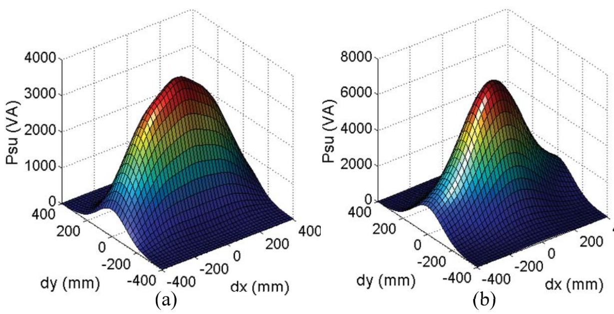

Fig. 5. Untuned output power of a DDQ secondary on a circular or DD topologies with lateral movement at 125-mm gap with $I_1 = 23A$ at 20 kHz. (a) DDQ on circular. (b) DDQ on DD.

gap spacing. Given the desire to be interoperable with many possible systems, the focus to date is on secondary systems as described following.

1) DDQ Coupler: As an example of such a mutlicoil pad the DD pickup may be converted to a DDQ coil by adding a third coil in quadrature [31], [33] and shown in Fig 4(a). This coil is also a flat Archimedean spiral essentially circular or slightly squarish coil that is placed symmetrically across the line of touching of the two original coils in the DD. If the two original coils (combined) are regarded as a single winding d-axis coil this third coil is a q-axis coil and the output of the (combined) d-axis coil is orthogonal (in quadrature) to the output of the new q-axis coil. It is a simple matter to increase the size of the q-axis coil to make its output commensurate with the d-axis giving a true d–q axes pickup. Thus, in a pickup situation comprising d and q components this pickup coil is sensitive to both of them and can take power from both of them as shown in Fig. 5. Here as shown, the use of this DDQ pad on a vehicle enables a power zone which is around three times larger irrespective of whether the ground pad is circular [see Fig. 5(a)] or polarized [see Fig. 5(b)], compared with that which can be achieved using matched circular—circular or matched polarized to polarized in Fig. 3. Notably, if a DD primary is used then coupling and power transfers are better suited to large air-gaps, but the ability to align the vehicle in any direction is not possible.

In another very important way, the DDQ pick up, however, may be seen as essentially a two-phase coil and it can be used with a three-phase excitation coil (under the road) if the wavelengths of the flux patterns are more or less equal as shown in similar research with AGV track systems [58], [59].

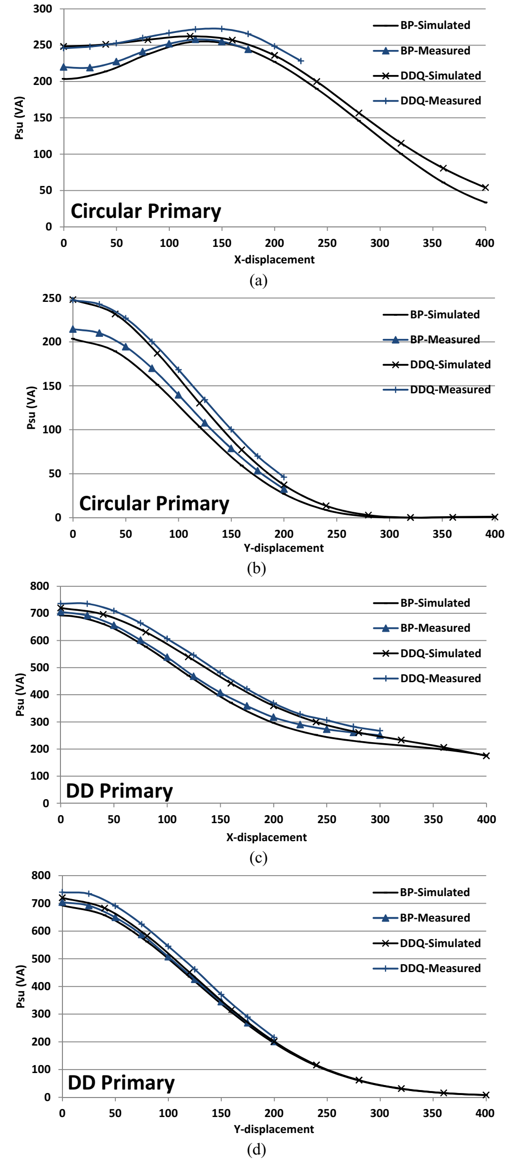

Fig. 6. Measured and simulated comparisons of un-tuned output power at 127 mm gap with lateral misalignment between pads. Each primary is energized with $I_1 = 15$ A at 20 kHz showing the performance of a DDQ or BP secondary on: (a) a circular primary with x-displacement, (b) a circular primary with y-displacement, (c) a DD primary with x-displacement, (d) a DD primary with y-displacement.

2) Bipolar Coupler: Another multicoil coupler called a bipolar (BP) design also includes magnetically independent coils [34] shown in Fig. 4(b). Its operation may be visualized by considering the two coils lying on the striated ferrite such that the line of centers is along the direction of the ferrite. If the coils are now made larger, but keeping the line of centers the same, then at some point where the two coils overlap they can be designed to be orthogonal to each other. At this point, the outputs from the two coils are uncorrelated and they can be used independently, and tuned independently, with independent outputs. As a secondary (vehicle) coupler, the output from a BP pad is almost identical (<10% difference) to that of the DDQ irrespective of whether it operates from a circular or DD primary, as shown in Fig. 6 [34], but this BP coupler uses between 25% and 30% less copper in its construction. While the DDQ is very versatile in that the Q coil can be made any size desired relative to the DD coil, here both coils of the BP must be identical. Nevertheless, it is also interoperable with either single-, two-phase or three-phase tracks or couplers. Naturally, either the DDQ or the BP coupler could be used as the primary (ground) pad and used to couple to any range of secondary (vehicle) pads. This would require a second synchronized power supply to enable the independent coils to be driven separately, but could then enable simple circular, solenoid or DD pads to be used on the vehicle side under stationary charging conditions.

E. Three-Phase Magnetic Systems

Today, the complete coupled system for an EV charger as described above is essentially a single phase one extending from a single-phase power supply driving a single-phase ground pad, coupled to a single-phase secondary pad with one or more coils under the vehicle, each with a single-phase resonant circuit and associated control. Alternatively, two- or three-phase systems may use two- or three-phase ground pads coupled to single-, two- or three-phase vehicle pads, and a variety of processing circuits. Two-phase pads such as the BP pad operating with currents in each coil at 90° as described in [32] were found to be less effective than the DD single-phase generator described above and require two synchronized generators. Three-phase ground pads may comprise three single-phase pads or one pad specially designed for three-phase operation and were proposed [74], [75] and applied in various commercial systems [76]–[78]. At present, it is not clear which is the better system. Single-phase systems are potentially lower cost but three-phase systems may produce better coupling results, particularly at higher powers, with larger air-gaps and possibly in dynamic applications, however, they are also necessarily large.

Three-phase IPT pickup systems operate in a similar fashion to three-phase linear induction motors except that the traveling magnetic field in an IPT system moves at such high speed that positive and negative sequences are not so important as the concept of slip has no meaning. Usually, with a three-phase system a three-phase generator would be used with a three-phase track and three-phase pickups, but as these pickups can be very large a better option may well be to use single-phase pickups with a DDQ or BP pickup to give continuous output power. Three-phase systems can also be used with a single-phase pickup covering $\sim$0.8 of one cycle of the ground pad's magnetic field pattern [75]. This single-phase option is convenient but it has implementation difficulties as the pickup can never present a balanced load to the three-phase primary and any unbalance shows as one phase with essentially resistive loading, and the other two phases with reactive loads—one capacitive and one inductive. The DDQ and BP pads present a better load to the track than a single coil structure given they are essentially two-phase systems, and while ideally their pole spacing should be optimized to match the track pole width, the variation in heights and power demands between classes of vehicles makes this optimization an on-going and significant challenge. Three-phase tracks may use three-wires in delta, or four wires in star, or six wires as three independent phases. Some of these wiring choices are particularly difficult to tune. But they can produce usefully high outputs and have found application in street cars and trains particularly where there is a known and fixed separation in the magnetics and room under the vehicle (such as in light rail or buses) to create a matched three-phase to three-phase system [77], [78].

VI. Powering EVs Wirelessly on the Move

As described above, IPT systems hold the promise of charging EVs without wires. Hands-free charging simply involves parking over a charging pad and the system will automatically connect and charge the battery in a process that is truly opportunistic and can be repeated many times per day whenever the vehicle is stationary, and the opportunity arises. In the most stringent stationary charging application for IPT systems so far, couplers used on a roadside must transfer power from a ground pad buried in the road to a pad in a vehicle some 250-mm above it with a possible misalignment of 150–200 mm in any direction. The coupling pads may be circular, elliptical, oval, or rectangular and today will usually have single sided coils to optimize their coupling efficiency and reduce the losses. As discussed in Section V, an obvious choice of pads is a DD pad on the ground with either a DDQ or BP pad on the vehicle. As noted, the pads do need a protective covering that is usually polyurethane on the car pad and a suitable material on the ground pad. The ground pad may need special strengthening if vehicle wheels can run over it as the fragile ferrite in its core is always an issue.

In a more challenging mode, power transfer may be established with the EV while it is being driven along the road in a lane that includes wiring to create a magnetic field that the vehicle drives above. This is the ultimate EV experience—an EV with no range anxiety, that does not need long charging times, and that is more efficient than any other EV can ever be as the power flow is essentially from the road directly to the wheel motors bypassing the battery that maintains its charge principally by scavenging energy as available. For systems to be developed and then installed with confidence by municipal or government authorities, several decisions, however, need to be made to ensure compatibility of the best magnetic couplers by the various suppliers and car manufacturers that are targeting this technology, particularly given the investment is likely to be high (perhaps as much as 10% of a highway lane) and needs to last for up to 30 years. Thus, the focus of new research is to determine not only the best frequency of operation (something that needs to be agreed across a number of interested parties), but also the power transfer rates/meter-squared over defined clearances and tolerances, a selection of robust magnetics that are compatible between various suppliers and suitable for the application (that includes light, medium, and potentially heavy duty vehicles) while size and weight limits also need to be addressed on board the vehicle. Despite the enormous challenges, this is an ideal situation that only IPT can possibly deliver, therefore steps toward it must be considered as discussed below.

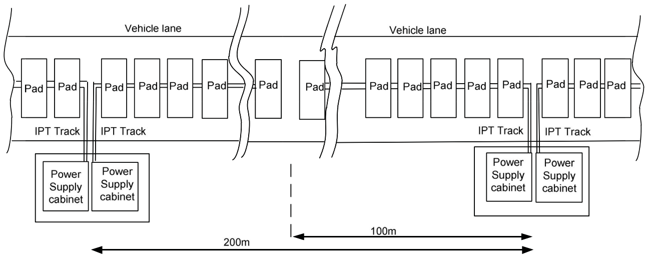

Fig. 7. Conceptual inductive roadway lane with separately energized pads.

The ability of these new polarized pads with two independent coils in the secondary to provide flux over a much wider surface makes them much better candidates for dynamic operation enabling a vehicle to travel from pad to pad coupling power dynamically as it proceeds. When operated from a DD primary, they are particularly tolerant to movement with lateral displacements in both x- and y-directions as shown in Fig. 6, hence the overall coupling stays high over the useful working area. With circular-to-circular pads this is not possible as the loss of coupling between the pads with even small movements reduces the power too much to make dynamic operation feasible [31].

Over the past two decades two particular developments worth noting have shown that inductive roadway power is possible. The KAIST system as recently proposed [42]–[45] uses essentially a polarized track configuration with long segmented track coils and polarized secondaries (similar to the DD) under the vehicle. Power nulls are noticeable when the vehicle secondary is operating between the poles pieces under the ground. The Bombardier system [77], [78] uses a three-phase magnetic track and can transfer power to large vehicles. Again the track lengths are long and well suited to large vehicles but not so well suited for smaller private vehicles. As proposed by Bolger [79] and Ross [80], energized track sections should be limited for efficiency reasons, and ideally these sections should be smaller than a vehicle's length to localize the power coupling and avoid energizing and heating unwanted loads [41]. This ensures that the system is efficient under operation but requires a larger number of smaller pads (perhaps as small as 1 m^2) to be laid down under the road and separately energized as each vehicle requiring or requesting power passes over it. The concept as shown in Fig. 7 suggests using an IPT system to provide energy under the roadway in an isolated and safe manner to intermediate power couplers under each pad in the roadway. This arrangement avoids using utility mains or dc under the roadway that is often prohibited for safety reasons in many countries. The pads can then be pulsed on directly under a moving vehicle at a set power level suitable for the vehicle traveling on the road (e.g., a higher current may be used for a vehicle demanding high power and a larger road clearance). This enables a wave of power to be created where the secondary is located where the coupling is strongest. Such power would need to be regulated on the vehicle side but as discussed in the control Section VII—a combination of primary and secondary control is by far the most efficient means of energy transfer. Further efficiency gains are, however, achieved if the power is delivered direct to the engine (perhaps through a super capacitor for smoothing) rather than to the battery, as there can be as much as 10%–20% loss in transferring energy into and out of modern battery packs [81]. As such IPT supplied direct to the power drive could well be as efficient as stationary charging even though the vehicle is not perfectly aligned. In addition, as shown by [40], such power control is the only means by which EVs can compete with ICEs in terms of range and efficient performance. The concept as discussed is validated using a laboratory scale setup in Fig. 8 using scaled versions of these DD pads at road-level and a DDQ secondary for the vehicle side pad. As discussed [82], the DD pads can be spaced appropriately to give a relatively smooth power profile over a wide tolerance, and while Fig. 8(c) shows the untuned power available with three ground pads turned on, in practice only two need to operate to transfer the required power. In Fig. 8(d), the evaluation was taken only to ±200 mm, however, the greatest power is coupled in the quadrature coil at 220-mm offset and it is possible to have misalignments even in this scaled prototype of up to ±300 mm. It is also possible to detect the relative misalignment of the vehicle on the road and use this to assist the driver to stay within this power transfer zone as is presently done for AGV systems in industry as discussed in Section IV. This research is continuing to determine the size of the couplers necessary for a roadway system at suitable power levels of up to 30–40 kW and beyond.

VII. Control of the IPT System

Controlling power flow in IPT systems is a problem common to virtually all IPT systems. In principle, there are three options available and choosing the best one may affect the efficiency by as much as 10%–20% as follows:

1) secondary side control;
2) primary side control;
3) a combination controller affecting both the primary and the secondary.

In early commercial applications of inductive power transfer, the object is to couple power to multiple loads operating off of a single track. As such the most common control approach is secondary side control where the track current and frequency are held nominally constant, and each secondary independently regulated its power as required by its load [3], [7]. This type of control essentially varies Q_2 and it is a reasonably efficient system but has high-loss in low-demand applications where the track current has to be maintained at all times even though no power is being transferred. In such cases, it is important that the secondary remains on tune so that the lowest Q_2 possible may be used to deliver the power demanded [83].

For charging applications where there is one supply for each coupled load, there is a tendency to operate using only primary side control [84]–[86]. This entails regulating both the primary current in the magnetic pad and also the frequency (if desired) to regulate the secondary—that usually has only a simple rectifier and filter. In consequence, there can be a considerable efficiency gain at light load over pure secondary control, but a wireless communication link between

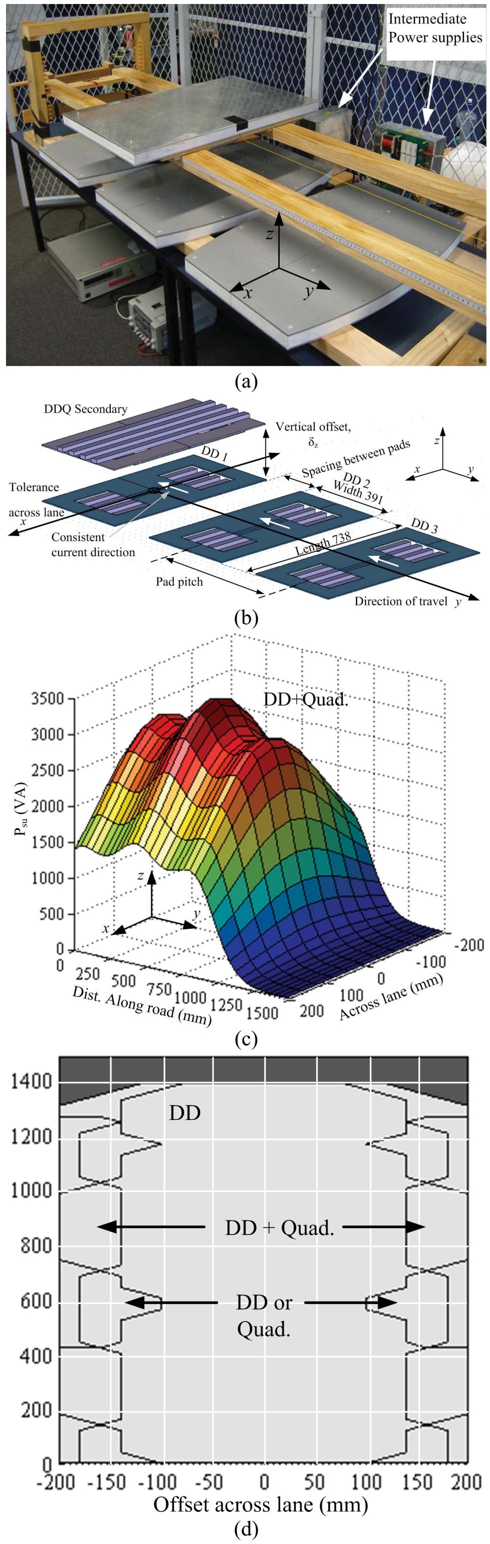

Fig. 8. (a) Experimental and (b) simulated laboratory scale setup of a roadway system comprising DDQ secondary on DD ground pads. (c) Measured and simulated untuned power (matching within 1%) with 23 A at 20 kHz in each DD pad with a pitch of 425 mm and pad clearance (σz) of 200 mm. (d) Possible 3.5-kW power zones with a $Q_2 = 6$ and $x \leq \pm 200$ mm showing which coil is required to provide power.

the primary and secondary is essential to enable safe power regulation. Generally, however, the secondary also needs a protection switch to shut off power in a system failure where too much power is found to be coupled—in such cases, a combination of primary and secondary side control is then possible without adding significantly to the cost. Primary side control on its own, is not desirable in multiple pickup materials handling systems given that this would vary the power transfer to all the pickups simultaneously and would be problematic in operation as a secondary needing more power would have to increase its operating Q_2 considerably, and increase its loss. This increase is limited in practice by the loss in each of the components in the resonant tank, and as such it may not be able to supply the needed power.

A controller that can vary both the track current and the secondary Q_2 so that the loss in the primary side is equal to the combined loss in all the secondary side controllers enables the best system of all [87]. This is useful in both materials handling and charging applications. For materials handling, under lightly loaded conditions the track current can be low and a small number of pickups will operate at a high Q_2 to obtain power—providing the track current remains sufficiently high to enable power to be delivered. In heavy load conditions, a larger track current may be used so that the pickups operate efficiently at a low Q_2. For charging applications it was shown [87] that the efficiency can be improved using a combination of both controllers to operate over a wide load range at $>90\%$.

A few controllers exercise control by simply allowing the frequency to vary and then choosing option 1, 2, or 3. These variable frequency systems can improve the efficiency by being perfectly tuned but are difficult to use in multiple pickup situations where the pickups are tuned at different frequencies. Other options include retuning the system using additional VAR correction mechanisms on either the primary or secondary side [3], however, these systems are often bulky and costly that is also undesirable. For dynamic IPT roadway applications, there is clearly no time to retune and therefore a variation of option 3 is preferred, where the roadway pad current is set for the vehicle power demand and the secondary controller regulates the power.

For stationary charging EV systems, there is now considerable research regarding means to enable EV loads to work as a controlled load on a smart grid. This is particularly desirable given it was shown [41], [88], that EVs balance the available green but fluctuable sources such as wind, wave, and solar that governments would like to use to increase the supply mix but that also create potential stability issues. Both bidirectional and unidirectional inductive options exist [41], [76], [88]–[91], although the extra electronics and power control necessary to enable bidirectional power flow needs to be justified, given unidirectional power flow can provide much of the benefits with little more than a smart control algorithm [92], [93]. For dynamic power transfer on highways, there is a little time available to consider power flow back to the mains, and unidirectional demand control is a simpler option with clear benefits.

VIII. Conclusion

This paper reviewed the challenge ahead to create low-cost inductively coupled EVs operating under stringent conditions that compared with the state-of-the-art 15 years ago require 10–100 times larger clearances and tolerances for similar or higher efficiency. Here, traditional circular pad technology is challenged by polarized pads giving greater height and versatility. A variety of such pads are available offering options that are interoperable with each other and with circular pads without a significant loss in power or efficiency. The more modern polarized pads and their combinations may be used for stationary charging (BEV) or dynamic charging (EV) without restrictions hence EVs on the road can be powered at high efficiency from renewables or any other source as they move. Progress from here will require the construction of pad sets that can last in a roadway for 30 years or more and continue to operate efficiently over their lifetime despite changes in technology.

Acknowledgment

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