Inductive Power Transfer

The historical background, technological issues, and engineering applications of inductive power transfer are presented in this paper. The authors also share their vision and arguments on the engineering challenges and future developments such as roadway powered systems.

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ABSTRACT | Inductive power transfer (IPT) was an engineering curiosity less than 30 years ago, but, at that time, it has grown to be an important technology in a variety of applications. The paper looks at the background to IPT and how its development was based on sound engineering principles leading on to factory automation and growing to a $1 billion industry in the process. Since then applications for the technology have diversified and at the same time become more technically challenging, especially for the static and dynamic charging of electric vehicles (EVs), where IPT offers possibilities that no other technology can match. Here, systems that are ten times more powerful, more tolerant of misalignment, safer, and more efficient may be achievable, and if they are, IPT can transform our society. The challenges are significant but the technology is promising.

KEYWORDS | Electric vehicles (EVs); inductive power transfer (IPT); resonant coupling; roadway-powered electric vehicles

I. INTRODUCTION

Inductive power transfer (IPT) has now grown from a fledgling technological base in 1995 to a $1 billion industry around the world today. IPT couples power from a track to a pickup coil on the receiver where both the track and the pickup coil are tuned at the operating frequency to enhance the power transfer. IPT finds application in factory automation, in clean factories (eFA) [1]–[10], for lighting applications [11]–[15], for instrumentation and electronic systems [16]–[34], in biomedical implants [35]–[39], in security systems, harsh environments, and lots of other applications where its unique features can be exploited [40]–[45]. The dynamic powering of vehicles on monorails has spread to floor mounted automatic guided vehicles (AGV) and other industrial vehicles for flexible manufacturing lines that can operate inside or outside, and in cool stores, and wet areas [46]–[55]. More recently applications for IPT have spread to the automotive industries where in the push for electrification of personal transportation systems IPT can offer some highly attractive possibilities [56]–[88]. These are hands-free charging systems that are unaffected by dirt, chemicals, or the weather and can, in principle, be extended to dynamic charging systems where a vehicle may be charged while it is in motion on an instrumented lane along the road [89]–[101]. Such systems offer convenience and reliability and surprisingly may well be the lowest cost of all private transportation options including conventional vehicles. But in achieving these features there are some significant difficulties that must be overcome. This paper reviews developments in the technology over the past two decades, which began with industrial applications but have recently shifted to designs that can meet the challenge of powering electric vehicles (EVs) under both stationary and dynamic conditions. This review begins with early designs focused principally on factory automation systems to power vehicles with constrained movement. In all such IPT systems thus far, energy has been coupled from a primary to a secondary across an air gap of significant but small proportions that stays relatively constant, even in the presence of movement. The primary coil on a monorail has the form of an elongated loop that is loosely coupled to a pickup coil on a vehicle and may transfer 1–10 kW of power across a 4–10-mm gap. With an AGV, the air gap may be 10–20 mm, and there may be a possible misalignment of similar magnitude (10–20 mm).

With the success of such systems, the focus of the last decade has been on developing systems that have improved tolerance to misalignment and can handle the variations in coupling which result. This has required improvements in magnetic design and control of power so that practical EV charging systems can now be considered for stationary charging systems without alignment aids, although

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dynamic power transfer to EVs on the move is still a challenge. Typical vehicles have air gaps between 150 and 300 mm, depending on size and application. If an EV has an air gap of 175 mm to the road, and the track system in the road has to be covered by 75 mm of bitumen, the *de facto* air gap is 250 mm. For such a vehicle, the required misalignments could easily be as high as ±300–600 mm. Furthermore, the vehicle may go on and off track as it moves along the road causing large changes in the magnetic circuits that couple the power from the roadway to the vehicle. These large changes present as changes in the inductances of the pickups and the track and make tuning the system difficult. In comparison with state of the art technology, IPT roadway requires power levels, air gaps, and misalignments that are all ten times higher, but the efficiency must also be very high as, for example, a track buried under the road surface cannot be cooled. Finally, the paper discusses many of the outstanding problems to be solved to enable widespread acceptance of the technology.

II. PREINDUSTRIAL IPT SYSTEMS

From the time of Ampere and Faraday and the founding of electric engineering based on their laws, the idea of wireless transmission of power has always been a goal. At high frequencies, work by Hertz where energy from a spark was coupled from one loop to another led ultimately to modern day radio systems, propagating power over large distances but with appallingly low efficiencies. Faraday's work led to direct current (dc) and alternating current (ac) machines which were greatly enhanced by the invention of the induction machine by Nikola Tesla and in all these cases power was coupled from a stator to a rotor and usually converted from electrical power to mechanical power at the same time. Here, the efficiency could be high, but the coupling distance was small and very constrained. Three-phase and single-phase transformers also couple power from one winding to another, but the coupling is again constrained and very short.

Experiments to couple power to moving trains were not successful but low-power signals could be transferred, and so the myth was propagated that wireless power transfer over large distances with a coupling that was tolerant of misalignment and air-gap size, and was unaffected by dirt, water, ice, or chemicals was not practically possible. Signals-yes, power-no, and this categorization persisted for more than 100 years. On the "signals" side, there have been significant developments with wired communications systems and inductive antennas, and noncontacting current sensors where the current in a wire is measured by measuring the magnetic field around the wire—Ampere's law—without making physical contact with the wire. But from a power point of view, there was no progress through the whole of the 19th century. At that time, there were very few ideas, and no technology to support them.

Perhaps the first real attempt to couple significant power was Hutin and Le-Blanc (U.S. Patent 527 857) who proposed an apparatus and method for powering an EV inductively in 1894 using an approximately 3-kHz ac generator. More recently, Otto [Provisional Patent NZ19720167422, JP49063111 (A)] proposed an inductively powered vehicle in 1972 using power generated at 10 kHz by a force commutated sinusoidal silicon controlled rectifier (SCR) inverter. His work proposed two spaced-apart circular cross-section conductors made of copper buried some 20 cm under the road, each carrying a current of 2000 A in opposing directions. The system had no controller; the pickup was series tuned, rectified, and connected directly to a dc drive motor. The work was abandoned, in 1974, but it did establish that power could be coupled to moving bodies.

Academic interest in IPT-powered EVs picked up in the late 1970s when, for example, Bolger, Ross, and others began publishing papers on electric highway systems [89]–[94]. A major project organized by The Partner for Advanced Transit and Highways (PATH) project in California was active through the 1980s, developing a roadway-powered IPT vehicle with a variable air gap [95]. The work achieved 60% efficiency powering a bus using machine generated electric power at 400 Hz coupled across the air gap to drive the bus. The air gap was controlled to be 50–100 mm when coupling power and 150–200 mm when not coupling power. Power control on the bus was achieved by capacitively detuning the pickup system, thereby placing a large volt.amps reactive (VAR) load on the generator, which the generator could easily supply at reduced efficiency. The project was later abandoned.

In 1986, Kelly and Owens proposed powering aircraft entertainment systems using wires under the carpet in the passenger bay of an aircraft. The system had essentially no controller [19]. A power supply generated a current at 38 kHz that was used to drive the wires, and pickups under each seat could couple 8 W for each passenger. Power for each passenger was regulated by essentially a large zener diode acting as a shunt regulator on each parallel-tuned pickup so that the generator ran at constant load but was very inefficient—for 120 passengers, there was a continuous combined load of 1 kW. The advantages of an IPT system were that all the seats could be taken out to convert to a cargo aircraft and there were no plugs and sockets that could get damaged in the process so that the turnaround time was significantly shortened. This innovation was followed by Turner and Roth (U.S. Patent 4 914 539) in 1990 using much the same infrastructure but with a controller on each parallel-tuned pickup circuit so that the VAR load on the pickup was varied to supply each entertainment system with a constant voltage. The system operated with constant resonant voltages on all the pickups, which conserved real power but placed a large VAR load on the generator under light loading conditions.

In 1991, Boys and Green at the University of Auckland produced an IPT system potentially suitable for materials handling and other applications (U.S. Patent 5 293 308). This patent became the cornerstone of much of the work in IPT systems over the past 20 years as it was the first systematic approach to an IPT system where the components of such systems could be identified, and separately improved. At the time of the development, the work was licensed to and funded by Daifuku Co. Ltd., so the development was compatible with Japanese regulations—in particular, the operating frequency was constrained to be below 10 kHz. The complete system included a resonant power supply driving an elongate inductor, parallel tuned with a capacitor, and a number of parallel-tuned pickups, each with its own decoupling controller, supplying power at nominally constant voltage to their particular load [2], [7]. The operating frequency was the ringing frequency of the elongate inductor with its tuning capacitor, and varied with temperature and with the VAR load reflected back to the elongate conductor as the load on the pickups varied. From the earliest time it was always thought that a vehicle driven by this technology would be constrained laterally by some form of track so the elongate inductor was called the "track," and this name is universally used.

In this work, the invention of "decoupling" solved perhaps the biggest problem in all IPT systems using naturally (load) resonant power supplies where the frequency is uncontrolled and allowed to vary at the natural frequency of the tuned circuit seen by the supply (including the load). Here with decoupling the pickup coil can be short-circuited (decoupled), or it can be fully tuned, taking full power from the track and supplying it to the load as described in Sections IV-A and IV-B. Without such control, if too many circuits are switched on and are lightly loaded, the track power supply will bifurcate and the system becomes unusable. Thus, bifurcation is a major problem which a decoupling controller can eliminate, enabling multiple independent loads to operate from a single track without interference.

In the light of these developments, the essential elements of an IPT system are:

1) a utility to VLF (very low frequency 3.0–30 kHz) or LF (low frequency 30–300kHz) power supply for energizing a track;
2) the track itself with its frequency compensation and magnetics construction methodology;
3) a pickup system for taking power magnetically from the track;
4) a controller for controlling the power transfer process to a dc output voltage.

III. DEVELOPMENT OF INDUSTRIAL IPT POWER SUPPLIES

At the present time, IPT power supplies typically operate from a three-phase utility to produce a current in the track at the desired frequency. This track current is commonly a constant current so that all pickups on the track have the same magnetic excitation. The track may be an elongate loop or one or more pads, and there may be one or more pickups operating from a given power supply at the same time. The track frequency may typically be anywhere in the range 5–140 kHz, although in lower power levels even higher frequencies may be used. In principle, there are two major power supply groupings that may be made and all power supplies belong in these groups [102]–[114]. The power supply either operates at a fixed frequency or a variable frequency, and the track inductance is either series compensated with a series capacitor, or it is parallel compensated. There are, therefore, four general types of power supply but sometimes these classifications may become quite blurred. Nonetheless, these classifications lead to characteristics that are beneficial or not to the IPT system and ultimately determine how useful that system is. Unfortunately, there are so many concepts and circuits for power supplies that in the space available it would be impossible to cover them all. Here, the requirements for a power supply are listed followed by a description of the earliest power supplies used widely in factory automation (FA) and clean FA. A discussion on power supply characteristics is then followed by the presentation of a modern IPT power supply.

A. Functions of an IPT System

A power supply takes power from a utility and energizes a primary loop or track to which pickup coils may be magnetically attached. A typical arrangement is shown in Fig. 1. In its most basic form, an IPT pickup consists of a coil of wire in close proximity to the track wires positioned to capture magnetic flux around the track conductor. A voltage is induced in this coil as described by Ampere's and Faraday's laws. Conceptually, this is very similar to a transformer, albeit with a much lower magnetic coupling. As in transformer design, magnetic material such as ferrite is used to direct the magnetic flux and improve the coupling between the track and any pickups.

The performance of an IPT pickup is primarily determined from two parameters [7]: the open circuit voltage induced in the pickup coil at frequency (ω) due to the primary track current (I_1), $V_{oc} = j\omega M I_1$, and its short circuit current $I_{sc} = M I_1 / L_2$, which is the maximum

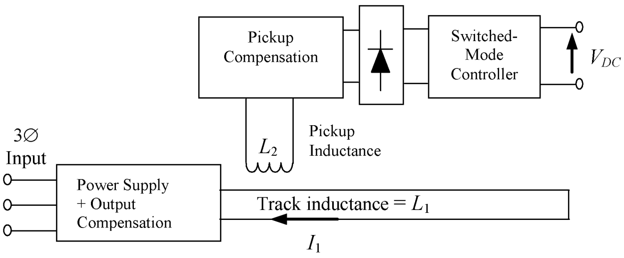


Fig. 1. *General arrangement for an IPT system.*

current from V_{oc} limited by the impedance of the pickup coil inductance ωL_2. Here, M is the mutual inductance between the track and the pickup coil.

The product of these two parameters results in the uncompensated VA of the pickup (S_u)

$$S_u = V_{\mathrm{oc}} I_{\mathrm{sc}} = \omega I_1^2 \frac{M^2}{L_2}. \tag{1}$$

Without compensation, the maximum power that can be drawn from a pickup is $S_u/2$, which is generally not sufficient. In order to improve the available power, the pickup inductor is compensated with capacitors such that it resonates at or near the frequency of the track (providing the frequency of the track does not vary considerably). Normally, the compensation capacitor (C_2) is applied either directly in series or in parallel, although parallel-tuned pickups are more common due to their inherent current limiting capabilities [7], [12]–[15], [115]–[118], [121]–[124], while more complex forms of tuning can be applied depending on desired response and expected operation [119], [120]. The ac tuning causes a resonant current to flow in the tuned L_2C_2 circuit, which is boosted by Q, while the voltage (V_c) across the capacitor is similarly boosted by the circuit Q. Here, Q is the tuned quality factor, which is determined by the output load or controller by controlling the output voltage/current [7].

Thus, for the parallel-tuned regulator, this tuning enables the output voltage seen by the regulator to be increased in proportion to the circuit's resonant Q, while for a series-tuned pickup, the output current is boosted by Q.

In either case, the output power into a load is thereby improved by $2Q$ resulting in

$$P_{\mathrm{out}} = S_u Q = \omega I_1^2 \frac{M^2}{L_2} Q. \tag{2}$$

In the case of the parallel-tuned circuit shown, the resonant current circulates in the L_2C_2 loop, and, thus, the pickup $VA = P_{\mathrm{out}}\sqrt{1+Q^2}$. This places a natural limit on Q since VA essentially increases with Q, while the bandwidth of the circuit reduces as a function of ω/Q.

While it is desirable to select tuning components with naturally high component Q's, practical factors such as the pickup VA rating, component tolerances, and aging affect the sensitivity and power transfer of the circuit, especially if the operational circuit Q is high. In consequence, this operating Q is normally designed to be less than ten for all practical operating conditions. Other means for improving the power transfer are by increasing the frequency or magnitude of the track current. Both these factors are limited by the ratings of semiconductor devices used in the power supply, and Litz wire used in the track and magnetic components. The remaining factors affecting power relate to the magnetic design of the pickup.

In a practical situation, the power transferred by such tuned circuits places an impedance (in Ohms) on the track based on the tuning topology [121]–[124]. When the system is operating at its tuned frequency, this can be described as

$$\begin{aligned} Z_L &= \frac{\omega M^2 Q}{L_2} \quad \text{series tuned} \\ Z_L &= \frac{\omega M^2 Q}{L_2} - \frac{j\omega M^2}{L_2} \quad \text{parallel tuned.} \end{aligned} \tag{3}$$

Thus, the track loading is purely resistive for series tuning but has a fixed reactive part for parallel tuning assuming the pickup is guided along a track and has constant M, as expected for monorail-based systems. In systems where the pickup can move lateral to the track or there is mistuning, then there will be additional VARs. The power supply must maintain a current in the track I_1 despite any variations in the VAR loading that can occur. In consequence, some work has been undertaken to control the VARs on either the pickup or the power supply side but such solutions generally involve adding to the cost and complexity of the system [125]–[128].

B. Power Supply Requirements

At its most basic level, a power supply should, therefore, include:

- an input rectifier and filtering system;
- an H bridge (or other) inverter section;
- an isolation transformer so that mains potential and frequency cannot be output;
- capacitor compensation for the track;
- a track-current controller.

C. Early IPT Power Supplies

At the time early experimental work with IPT was undertaken, power electronics was still the domain of force commutated SCR converter circuits and power transistors were promising but primitive. In consequence, the use of SCR circuits could be avoided but the power handling capacity of the circuits had to be managed as much as it was possible so that the transistors only switched the real power while the track VA was significantly larger. Several resonant circuit topologies had this ability and a circuit using a dc voltage source (formed by simple rectification of a three-phase utility) with a dc inductor and a phase splitting transformer, a resonant parallel-tuned track, and only two power electronics switches was chosen and is shown in Fig. 2(a) [102]. This circuit does not meet the requirements listed above but it does produce a very low distortion sine wave output and maintains efficiency by having zero voltage switching and nearly zero current switching as

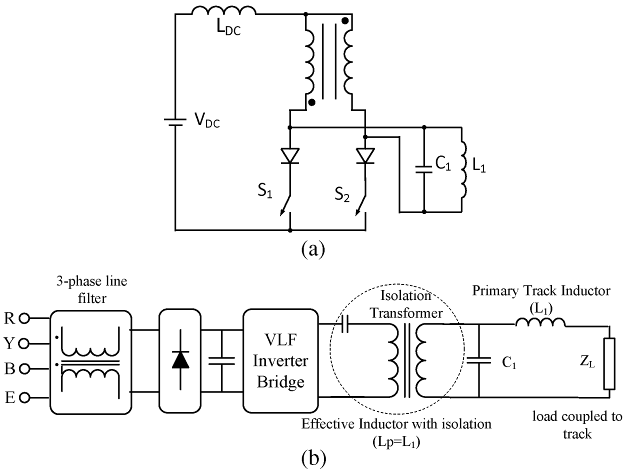


Fig. 2. ***Typical IPT power supplies: (a) a current sourced naturally resonant converter; and (b) a fixed frequency LCL-tuned system with built-in isolation.***

the switch current is typically five to ten times lower than the track current. If the circuit can be kept perfectly tuned, the diodes in series with the switches can be eliminated, but, in fact, they are always added as perfect tuning in an IPT system is never achievable. The circuit has a feature in that the output peak voltage is π times the dc input voltage so that it is particularly useful in countries like Japan where the utility voltage is low as the higher output voltage allows longer tracks to be driven. Where the utility voltage is high, a version of the circuit without a phase splitter is preferable. However, while this resonant circuit allowed IPT systems to be built, it had a number of severe difficulties. The track current is directly determined by the utility voltage and is not dynamically variable. To maintain zero voltage switching requires the circuit to follow the resonant frequency as it varies with load on the system and under light loading the circuit will bifurcate and run off-frequency at much lower power. The circuit is difficult to start and to stop and protection from overload conditions and bifurcation is challenging as the switches cannot be switched off when there is any current in the dc inductor—the normal condition. The circuit is not isolated from the utility and presents a significant hazard in operation.

As the state of the art in power transistors, improved hard-switching transistors on 700-V bus bars became feasible and a far wider choice of power supply circuits began to be used. These transistors were developed for the ac motor control market but they allowed switching rates of 20 kHz and more and made the complete control of IPT systems possible. In particular, IPT systems could now be operated at a fixed frequency as the VAR loads could be switched by the transistors, and resonant tracks could be switched on and off under complete control. As transistor switches continue to improve, the operating frequencies can become higher still so that IPT systems can be smaller, limited now by the ratings of the capacitors. Today, it is feasible to envisage an IPT system where the track is not resonant, but, at present, such systems would still be too inefficient to be able to compete with resonant tracks and resonant pickups.

D. Modern Power Supplies

With the improvement in transistors there was real choice: power supplies could be fixed frequency or variable frequency, and the track could be series or parallel tuned. Series-tuned tracks have a particular attraction as in principle they have no VAR load and the track current can be controlled by operating near but not at a perfect resonance condition, and varying the output voltage of the H bridge to hold the current constant over a wide range of loading conditions. This control is lost if the VAR load on the track is too severe. The ability to directly control the current comes at a high cost as that current must go through the switches so the power supply loses efficiency on light loads.

The question of variable or fixed frequency operation is difficult. In systems coupling one power pad to another with widely varying parameters, there are significant advantages in a variable frequency as small changes in the frequency can tune out VAR loadings and make the operation more efficient. The system cannot allow the frequency to change automatically or the IPT system may bifurcate and significant power transfer will be lost, but selected fixed frequencies can be chosen to achieve a much better result without difficulty. In a monorail situation, the frequency cannot really be altered to suit a multiplicity of pickups but the chances of bifurcation can be reduced by using controllers on the pickups such that when they are lightly loaded the pickups run at very low Q or indeed switch off completely, and in the process maintain a constant VAR load on the power supply. These situations apart from the economics of IPT systems mean that they must in general be reasonably loaded, and under high loading conditions the only real guarantee against bifurcation is a fixed frequency system. New power transistor families such as generation 6 insulated gate bipolar transistors (IGBTs) and silicon carbide (SiC) metal–oxide–semiconductor field-effect transistors (MOSFETs) with diodes that have negligible recovered charge allow H bridges to switch VAR loads without difficulty at frequencies up to more than 50 kHz and make fixed frequency switching the clear choice for most IPT power supply applications. A circuit diagram for a power supply that meets the requirements listed above is given in Fig. 2(b).

This power supply has an input line filter for preventing electro-magnetic interference (EMI) propagating back to the utility followed by a conventional line filter and a three-phase bridge using six fast recovery diodes to reduce EMI generation.

Unlike motor control circuits, the frequency of operation is high, typically 20 kHz, so that the filter capacitor can be surprisingly small, in the order of 2 μF per kW for the power supply. The very small capacitor means that the power supply can be started direct-on-line (DOL) without concerns for the inrush current, and fault currents in the inverter are small so that device failures do very little damage to other components. There is no dc inductor which improves both the power factor and the efficiency by 1%–2% [111], [113]. The *H* bridge is conventional and is followed by an isolation transformer driving a track inductor in parallel with a tuning capacitor. On load the resonating current for track L_1 is supplied by the tuning capacitor (C_1) and the real power is supplied by the *H* bridge. The connection from the *H* bridge to the primary of the transformer includes the leakage inductance of the transformer, a fixed inductor if required, and a series capacitor if required such that the total impedance in the connection path is inductive (L_p) with the same reactance, referred to the secondary, as the track. Thus, referred to the secondary side of the transformer there is an inductor–capacitor–inductor (LCL) impedance converting network [105]–[114], such that a constant voltage from the *H* bridge produces a constant track current virtually free of harmonics. The track current may be altered or switched on or off simply by changing the duty cycle of the *H* bridge.

The circuit has the advantage that the leakage inductance of the transformer is constructively incorporated into the circuit and assists in filtering the harmonics and in creating the current source in the track.

IV. APPLICATIONS USING MULTIPLE PICKUPS ON A TRACK

A. The Decoupling Controller

A typical IPT system as applied to materials handling systems is composed of a primary track made up of an elongated loop of wire which may be series compensated to ensure that the inductance is within the limits able to be driven by the power supply. The supply and track are required to provide power to a number of independent loads, each of which couples to the track using a pickup inductor placed in proximity to the track wires. These coupled loads are distributed along the track and each pickup is designed to be nominally resonant at the frequency of the track supply. The output of each tuned circuit is then rectified and regulated to ensure a controlled dc output at a voltage and power level suitable for the chosen load, but the early challenge was to ensure that all of these units were completely independent given each must couple different amounts of power depending on the operation required of it at the time. As described in Section II, a solution to independent control of a pickup is to include a decoupling controller which enables both regulation of power and control of the reflected load back to the primary, and this is shown in the circuit of Fig. 3 [7].

The concept of a decoupling controller was introduced in Section II but not described in detail. Fig. 3 shows an example of the original patented decoupling controller for a parallel-tuned pickup. Other relevant decoupling controllers have also been described [119]. As shown, the output of the tuned circuit is rectified and filtered using a dc inductor (L_{dc}) and capacitor (C_{dc}). These values are chosen for the application in mind, but, in particular, it is desirable to guarantee that L_{dc} is sufficiently large to ensure the diodes remain in conduction for the majority of the expected loads [115], [116]. Series-tuned circuits have also been discussed [117]–[119] and can be used to achieve similar results.

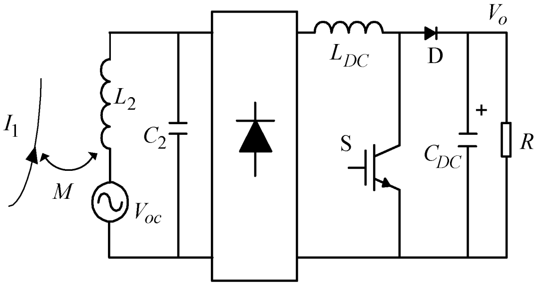


Fig. 3. *Decoupling controller for a parallel-tuned pickup coupled to a track carrying current I_1.*

Switch *S* in Fig. 3 is used to decouple the pickup by completely short-circuiting the coil (power flow is shut off to the load and the resonance in the ac circuit dies so that only the short-circuit current of the winding flows through this switch), and under such conditions the load reflected back to the track corresponds to a small section of track being short-circuited putting a small VAR load on the track, as described in (3).

In fact, with parallel tuning, the reflected VAR load on the track is constant for all (tuned) loading conditions (assuming the relative position of the receiver relative to the track is constant as in monorail-based systems) and a small VAR load is only apparent if the pickup coil is physically removed from the track. To the track circuit, the action of the decoupling switch is, therefore, to make the pickup appear to not be there.

Thus, if all lightly loaded pickups are decoupled, the problem of bifurcation is eliminated. In the second aspect, the decoupling switch may be used as a controller. If the output of each pickup controller is a dc voltage on a capacitor, then a simple control strategy is to decouple the circuit when the output voltage is high and recouple it when the output voltage is low. A small hysteresis band may be used to set the control frequency to perhaps 100 Hz. Alternatively, state–space averaging may be used to analyze the circuit switching at high speed (20–30 kHz) and control the output voltage as required by varying the duty cycle *D* of the switch [115]. These two aspects of the action of a decoupling switch (preventing bifurcation and voltage control) are the very essence of controlling an IPT system so that the real power is varied without affecting the VAR load.

B. Development of Monorail and AGV Applications

In the majority of material handing applications, the pickup 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 traveling motor to move the bogie along the 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 pickup uses magnetic material such as ferrite to improve the local coupling, and, hence, 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 either *U*- or *E*-shaped pickups [6], [7] (an example of the *E*-shaped pickup is shown in Fig. 4) since these pickup shapes were readily available and easy to fit into existing structures.

With the advent of suitable 3-D finite element modeling packages (such as JMAG Studio), the magnetic design of the pickup structure was able to be investigated, enabling new and improved magnetic structures to be rapidly explored, from which a number of new asymmetrical magnetic topologies suitable for track systems were proposed. Of all of these, the *S*-pickup shape was shown to have significantly higher power transfer capability than both the conventional *E* and *U* shapes (by a factor of 2 for the same volume of ferrite as *E*) but its uptake by industry has been slow because this design requires significant modification to the monorail support system in which most applications are fitted [Fig. 4(b)], given traditional track supports interfere with the *S* pickup in moving applications [9].

The magnetic design of pickups which are used for AGVs, robots, 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 the pickup designs are normally flat, as shown in Fig. 5(a) and (b) [46], [49].

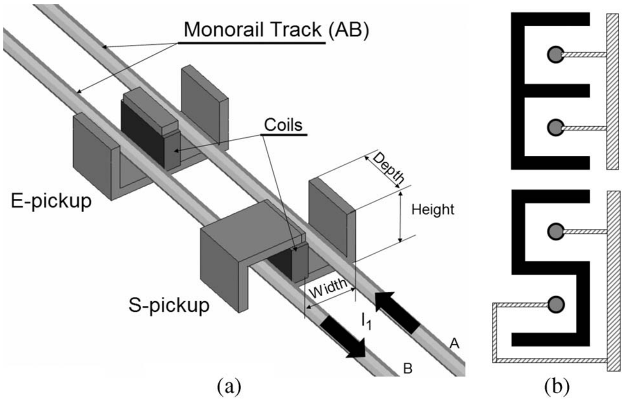


Fig. 4. ***(a) The E and S power pickups as positioned along a track section. (b) Cross sections of pickup and track with added support structures.***

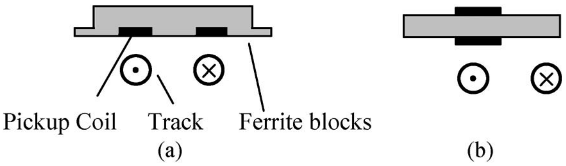


Fig. 5. ***Common pickup for AGVs with constrained movement: (a) flat-E, and (b) flat-bar pickup.***

Bipolar (rather than unipolar) tracks as shown are usually preferred in commercial applications, due to the natural return path and consequent limit on radiated fields. The flat pickup designs and coil placement of Fig. 5 are separately optimized to capture either the vertical [Fig. 5(a)] or horizontal [Fig. 5(b)] component of flux around the primary cable, and are shown here in the position which would enable them to capture the maximum flux for a given height. For single-phase bipolar track systems, when the pickup moves laterally with respect to the track, null points exist in the power profile irrespective of the magnetic field component chosen. For the vertical pickup, power nulls exist above each of the conductors but its maximum is in the center where it captures flux contributions from both conductors. The horizontal bar-shaped pickup has a power null that exists in the center of the track, and maxima which ideally exist directly above each conductor.

In practice, both are sensitive to any misalignment, however, the vertical pickup is preferred as it couples more power but it is most sensitive to movement and typical tolerances to movement for gaps between the track and the pickup of between 10 and 20 mm are only 10–20 mm laterally.

Over the last decade, there has been a desire to enable improved freedom of movement for such systems by changing the number of track wires, their geometry, and the relative phase of their currents [46]–[52]. Track solutions include repeated or meander track layouts, which still contain areas of low power delivery. A variation of this employs sequentially excited track sections, which require vehicle sensing and switching primary coils [47], [48]. These systems usually require some form of onboard storage to manage fluctuations and facilitate starting [24], [41], [47], [93]. Recently, polyphase track configurations have been employed to compensate for misalignment by producing a traveling magnetic wave [49]–[52]. The disadvantage of such systems is the cost and complexity of the power supplies and installation required for multiple phases, however, the pickups onboard the vehicles are relatively simple, and there is the possibility to achieve improved transfer to the secondary power receiver if the

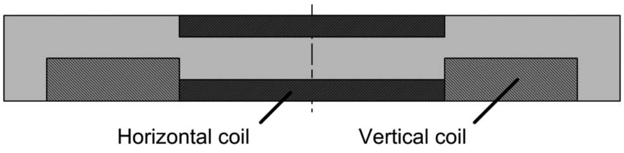


Fig. 6. *Example of a modified flat E with two coils called the flush quadrature.*

system is well designed while providing significant lateral tolerance. Of the various track topologies proposed, the simplest is the single phase track while the most promising from the point of view of enabling constant power transfer over a wide power zone is a multiphase system that produces a time-varying magnetic field around the track conductors. This significantly improves the coupling between the pickup and the track, allowing significant improvements to lateral tolerance compared to other approaches. In conjunction with this, changes to the pickup magnetic structure have also been investigated; the most promising of these is a two-coil receiver called the quadrature pickup [53]. As described, such a pickup enables power to be coupled from both vertical and horizontal components of flux, each of which exists above both single or multiphase track systems, so that the tolerance and performance of any pickup receiver can be improved. An example of such a magnetic pickup is shown in Fig. 6. Magnetic design and electronic optimization can be employed to ensure the best coupling of the available vertical and horizontal flux components, while the controller as described earlier can be simply modified to ensure good steady state and transient operation and efficiency [54]. Surprisingly, the impact on a power supply tuning and operation is improved as a result of using a quadrature receiver over the “simpler” designs, shown in Fig. 5, with little or no loss in efficiency but the additional tuning electronics and rectifier must be included. The only difference between a standard pickup controller and the controller required for a quadrature pickup is that, here, two windings are placed on the pickup receiver and individually tuned, rectified, and added together before being controlled on the load side.

When such a receiver is used on a simple track, rated power transfer can be delivered with six times improvement to the lateral tolerance of the pickup receiver 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 [53]–[55].

V. LUMPED CHARGING PAD APPLICATIONS

Lumped charging systems for applications for higher power have also seen considerable development over the past two decades, beginning with plug-in inductive systems [56]–[62], followed by solutions that have gradually enabled air gaps and tolerances required by the EV industry to enable hands-free charging [63]–[88]. In such applications, the primary and secondary magnetic systems are often either very similar or identical, and generally both use ferrite to enhance power transfer. As a consequence, the demands on the supply can be even more challenging, given that there can be considerable lateral and vertical misalignment from what might be considered ideal, due to variations in parking, vehicle loading, and ground clearance of various vehicles. These variations result in changes to not only M but also L_1 and L_2, so that some 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 lower than 1 may be enough, and, as such, the system has a wider bandwidth and can sustain greater mistuning. Despite this, such variations make power transfer challenging, and, in consequence, most IPT charging systems have one power supply for each coupled load, so that both I_1 and the supply frequency can be adjusted to help compensate these variations.

As described in (2), the power output of an IPT system is quantified in terms of V_{oc}, I_{sc}, and the operating Q of the receiver circuit. When considering lumped systems, it is helpful to rewrite this in terms of the VA at the input terminals of the primary pad ($V_{\mathrm{in}}I_1$), the transformer coupling coefficient (k), and the operating Q of the secondary

$$P_{\mathrm{out}} = P_{\mathrm{su}}Q = V_{\mathrm{in}}I_1k^2Q. \tag{4}$$

The coupling coefficient provides a useful measure for directly comparing the magnetic properties of different pad topologies and can be easily determined by taking a few measurements with an inductor–capacitor–resistor (LCR) meter. When comparing various topologies, the secondary operating Q can be temporarily ignored to decouple the magnetic design and the output power. In practice, the pad input voltage is often limited by regulation placing a constraint on the maximum VA of the primary. Consequently, P_{su} is highly dependent on k, and designs that have maximal k at a given air gap are preferable. Currently, EV manufactures are concentrating on small urban vehicles, and these typically have very low ground clearances, so that the required air gap between couplers can be as small as 100 mm and as large as 280 mm. There is an implicit change in the driving VA as inductances vary with pad movement or design [81]. In practice, the desired VA can be limited by adding series capacitance to the primary pad to effectively lower the inductance seen by the supply, however, the amount that can be practically added is limited because it also increases the tuning sensitivity. As

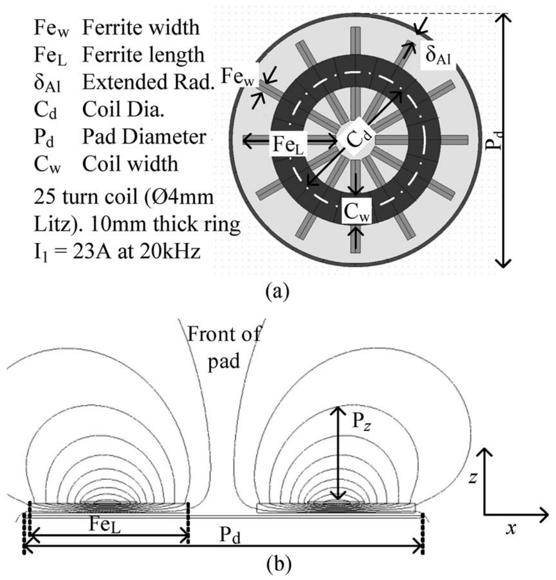


Fig. 7. *(a) Typical layout of a circular power pad. (b) Typical fields.*

shown in various papers, the peaks in P_{su} and k do not usually occur at the same design point [81], [83], [85]. As a result, selecting a pad design that meets performance requirements (e.g., 7 kVA) typically requires a compromise in k and the VA required to drive L_1.

To date, circular designs are by far the most common coupler topology used for EV charging; these are the most intuitive and have been derived from pot cores [59], [61], [64], [76], [80]. Circular power pads have been developed using ferrite disks and spokes in [65], [67], [81], and [81], focused on optimization of ferrite use and layout for a pad measuring 700 mm in diameter, built using readily available I93 cores (three per radial strip). The layout was similar to that shown in Fig. 7. High power pad efficiency is a critical component in ensuring that the overall system efficiency is acceptable. The loss in a pad is easily quantified by the native quality factor of the inductor coil Q_L, which is the ratio of its impedance to its ac resistance at the operational frequency ($Q_L = \omega L/r_{ac}$). This accounts for iron loss in the ferrite and eddy current loss in the aluminum. For example, the 700-mm circular diameter pads presented in [81] and [85] had a Q_L of 291 at 20 kHz and an inductance 542 uH. This corresponds to a loss of 124 W when driven with a current (I_1) of 23 Arms. The loss in the receiver pad is often lower or similar given the resonant current is significantly lower than 23 A. The aluminium backing and ring add robustness and provide shielding around the pad to any leakage fluxes which exist. As shown in [88], the extended radius δAl should be sufficient to help reduce field leakage to meet the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines [129], [130] without contributing unnecessarily to loss.

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 in [83] and [85]. This is illustrated in Fig. 7 where a cross section of a simulated energized circular pad is shown. The fundamental flux path height (Pz) is approximately proportional to half of the ferrite length, which is one quarter of the pad diameter (Pd/4).

Consequently, polarized couplers have recently been investigated based on shaped bar ferrites, as these have a flux path height approximately proportional to 1/2 of the pad length [82]–[88], [101]. Early topologies [82]–[84], [87] are essentially flattened solenoids and produce equal flux paths on both sides of the pad and are, therefore, not as desirable as the single-sided topologies of [85], [86], [88], and [101].

An example of one of these new single-sided flux pad topologies is shown in Fig. 8 [85]. It has been labeled a *DD* because of the ideal *D* shape of the coils sitting on the ferrite base. The improvement is a result of two development stages that eliminate 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 radiate on one side. Therefore, the aluminum only needs to shield stray fields, resulting in negligible loss. The ideal flux paths are also shown, and these paths allow good coupling to a similarly shaped receiver because the fundamental height (h_z) is proportional to 1/2 of the pad length. A key feature to achieving a high coupling factor between two power pads is intrapad coupling k_{ip} [85]. The height of the intrapad flux (ϕ_{ip}) is controlled by adjusting the width of the coils in the shaded area of Fig. 8, to create a "flux pipe" between coils *a* and *b*. The fraction of flux ϕ_{ip} that couples with the secondary pad is mutual flux (ϕ_M), therefore, the section of 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 r_{ac}. As constructed,

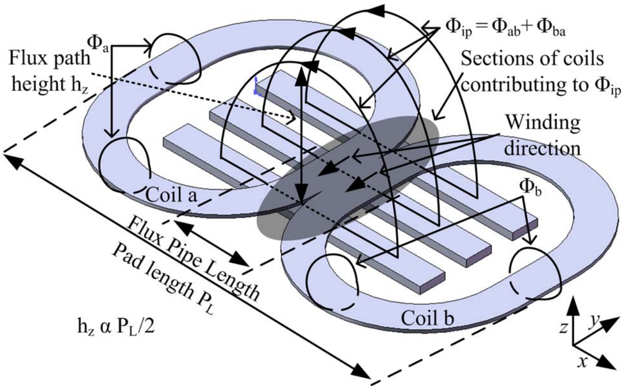


Fig. 8. *A simplified model of a* DD *pad with main flux components ϕ_a, ϕ_b, and ϕ_{ip}, produced by coil* a*, coil* b*, and mutual coupling, respectively.*

the *DD* primary surface area is 0.32 m^2, and it has an inductance of 589 uH, and a Q_L of 392 at 20 kHz [85].

As the secondary (receiver), *DD* coils can only couple horizontal flux components, and as such the tolerance of the receiver pad to horizontal offsets in the x-direction can be significantly improved if the second receiver coil is added, similar to [53] and [54]. This spatial quadrature coil should be designed and optimized along with the *DD* structure using the design parameters shown in Fig. 9 to balance the capture of vertical and horizontal flux in a similar way to the quadrature receivers developed for materials handling systems. The additional coil requires lengthened ferrite strips to enhance flux capture and the combined structure is referred to as a *DDQ* [88].

Charge zones define the physical operating region where the desired power can be delivered given a particular air gap and operational Q. If a maximum operating Q of 6 is assumed and the air gap is set to 125 mm, the results of a *DDQ* receiver pad operating with a *DD* transmitter can be compared with this same pad operating with a circular pad, which has a slightly larger area, but similar inductance, and is driven under identical conditions [88]. The potential charge zones for both systems are shown in Fig. 10(a) and (b). For comparison, the charge zone from the circular on circular is also show as "*C* on *C*." Notably, the physically smaller *DDQ–DD* pads significantly outperform the circular pads. A *DD* alone provides a charge zone large enough to enable parking without electronic guidance. Either the quadrature or *DD* coil can be used to supply the full output power in the regions where the *DD* and quadrature charge zones overlap.

The region outside the explicit *DD* and quadrature charge zones [indicated by $DD + Q$ in Fig. 10(a)] shows the output of either coil is not enough to provide the desired 7 kW, but when both coils are combined, the power output is ≥ 7 kW. The charge zone for a *DDQ* on a circular pad is shown in Fig. 10(b); this is a far larger zone than that possible with circular pads only. The *DDQ* receiver is considered to be completely interoperable with systems based on circular pads, and, as shown, an EV will fundamentally have more tolerance.

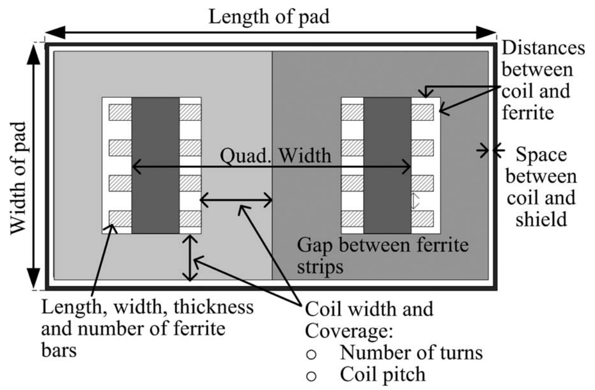
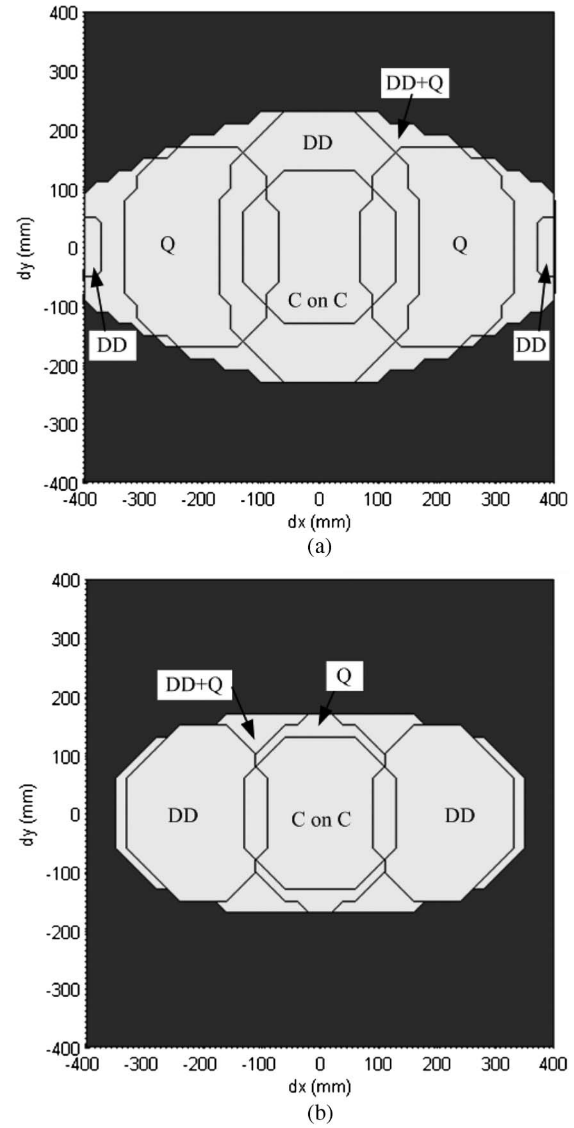


Fig. 9. ***Pad design variables for a*** *DDQ* ***receiver.***



(a)

(b)

Fig. 10. ***Seven-kilowatt charge zones at 125-mm separation for different pad combinations*** ($Q_{max} = 6$). ***(a) Circular on circular and*** *DDQ* ***on*** *DD*. ***(b) Circular on circular and*** *DDQ* ***on circular*** ($I_1 = 23$ ***A at 20 kHz).***

VI. FUTURE ROADWAY-POWERED SYSTEMS

Unlimited EV range can be realized with a dynamic charging system, however, the receiver on the EV must work equally well with both stationary and moving transmitter pads. Circular pads are not suitable for dynamic charging as they have a null in their power profiles when horizontally offset by 38% of the pad diameter [81]. This null occurs within the pad diameter, so even if transmitter pads are touching along a highway, it is not possible to obtain a smooth power profile. Multiple lines of pads offset to produce on average an even profile with multiple receivers could be implemented but are not economically feasible, given the gaps between pads are likely to be larger for highway systems and require very large circular pads to couple the required distance. A concept where multiple transmitter pads produce a continuous magnetic field when laid in a row was presented in [98]. The new couplers of [85] and [86] are suitable and could be used to meet both stationary and dynamic requirements for roadway-powered applications because the power zone is reasonably smooth in the *y*-axis. In practice, the pads would need to be scaled in size [85] to meet the 20–60 kW required for charging and propelling a vehicle [96], but this would offer significant advantages which would make EVs more cost effective than internal combustion engine vehicles (ICEs) [97]. To illustrate the concept, noting larger sized *DD* pads are required, these pads could be buried under a road and orientated so that the width of the pad (shown in Fig. 9) is in the direction of travel (along the *y*-axis). The *DD*'s presented here are only 410 mm wide and 7 kW can easily be transferred when the *DDQ* receiver is offset by 205 mm in the *y*-axis. At this point, the *DDQ* receiver is also effectively offset from an adjacent transmitter by 205 mm in the *y*-axis, therefore, continuous power could be provided to the EV. Note that at that point the power is likely to be significantly greater than 7 kW due to the contribution from both pads, thus permitting the transmitter pads to be positioned in the road with a gap between them. This will lower the cost of the system, given fewer pads are needed per kilometer of road regardless of size.

Other roadway systems are under development, an example of which is described by Meins *et al.* in various patent applications WO2010/000494 and 495. This includes a distributed three-phase track with large three-phase pickups for road and rail applications. The system has excellent performance but is expensive and uses a lot of ferrite in the road. Various innovative online EV systems have been developed by KAIST (Daejeon, Korea) with high power transfer and low emissions [99]–[101]. The latest uses 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 pickups and achieves excellent flux leakage conditions significantly lower than ICNIRP recommendations [129]. It uses 1–60-m-long segmented track sections with a lot of ferrite in it and is applicable to personal vehicles and public transport buses. Both of these systems have been through more than one generation, and the technology in them has improved markedly both in performance and cost in each generation so that roadway-powered EVs are now starting to challenge traditional vehicles.

The problem areas to be solved are cost and 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. ■

REFERENCES

[1] E. Abel and S. Third, "Contactless power transfer-An exercise in topology," *IEEE Trans. Magn.*, vol. MAG-20, no. 5, pp. 1813–1815, Sep.–Nov. 1984.

[2] A. W. Green and J. T. Boys, "10 kHz inductively coupled power transfer-concept and control," in *Proc. 5th Int. Conf. Power Electron. Variable-Speed Drives*, Oct. 1994, pp. 694–699.

[3] Y. Hiraga, J. Hirai, A. Kawamura, I. Ishoka, Y. Kaku, and Y. Nitta, "Decentralised control of machines with the use of inductive transmission of power and signal," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, 1994, vol. 29, pp. 875–881.

[4] A. Kawamura, K. Ishioka, and J. Hirai, "Wireless transmission of power and information through one high-frequency resonant AC link inverter for robot manipulator applications," *IEEE Trans. Ind. Appl.*, vol. 32, no. 3, pp. 503–508, May/Jun. 1996.

[5] J. M. Barnard, J. A. Ferreira, and J. D. van Wyk, "Sliding transformers for linear contactless power delivery," *IEEE Trans. Ind. Electron.*, vol. 44, no. 6, pp. 774–779, Dec. 1997.

[6] D. A. G. Pedder, A. D. Brown, and J. A. Skinner, "A contactless electrical energy transmission system," *IEEE Trans. Ind. Electron.*, vol. 46, no. 1, pp. 23–30, Feb. 1999.

[7] J. T. Boys, G. A. Covic, and A. W. Green, "Stability and control of inductively coupled power transfer systems," *Inst. Electr. Eng. Proc.—Electr. Power Appl.*, vol. 147, no. 1, pp. 37–43, 2000.

[8] K. I. Woo, H. S. Park, Y. H. Choo, and K. H. Kim, "Contactless energy transmission system for linear servo motor," *IEEE Trans. Magn.*, vol. 41, no. 5, pp. 1596–1599, May 2005.

[9] G. A. J. Elliott, G. A. Covic, D. Kacprzak, and J. T. Boys, "A new concept: Asymmetrical pick-ups for inductively coupled power transfer monorail systems," *IEEE Trans. Magn.*, vol. 42, no. 10, pp. 3389–3391, Oct. 2006.

[10] P. Sergeant and A. Van den Bossche, "Inductive coupler for contactless power transmission," *IET Electr. Power Appl.*, vol. 2, pp. 1–7, 2008.

[11] J. T. Boys and A. W. Green, "Intelligent road studs—Lighting the paths of the future," *IPENZ Trans.*, vol. 24, no. 1, pp. 33–40, 1997.

[12] H. H. Wu, G. A. Covic, and J. T. Boys, "An AC processing pickup for IPT systems," *IEEE Trans. Power Electron. Soc.*, vol. 25, no. 5, pp. 1275–1284, May 2010.

[13] H. H. Wu, G. A. Covic, J. T. Boys, and D. Robertson, "A series tuned AC processing pickup," *IEEE Trans. Power Electron. Soc.*, vol. 26, no. 1, pp. 98–109, Jan. 2011.

[14] D. Robertson, A. Chu, A. Sabitov, and G. A. Covic, "High powered IPT stage lighting controller," in *Proc. IEEE Int. Symp. Ind. Electron.*, Gdansk, Poland, Jun. 27–30, 2011, pp. 1974–1979.

[15] J. E. I. James, A. Chu, A. Sabitov, D. Robertson, and G. A. Covic, "A series tuned high power IPT stage lighting controller," in *Proc. IEEE Energy Conv. Congr. Expo.*, Phoenix, AZ, USA, Sep. 17–22, 2011, pp. 2843–2849.

[16] A. W. Kelly and W. R. Owens, "Connectorless power supply for an air-craft passenger entertainment system," *IEEE Trans. Power Electron.*, vol. 4, no. 3, pp. 384–354, Jul. 1989.

[17] A. Esser and H. Skudelny, "A new approach to power supplies for robots," *IEEE Trans. Ind. Appl.*, vol. 27, no. 5, pp. 872–875, Sep./Oct. 1991.

[18] S. I. Adachi, F. Sato, S. Kikuchi, and H. Matsuki, "Consideration of contactless power station with selective excitation to moving robot," *IEEE Trans. Magn.*, vol. 35, no. 5, pt. 2, pp. 3583–3585, Sep. 1999.

[19] Y. Jang and M. M. Jovanovic, "A contactless electrical energy transmission system for portable-telephone battery chargers," in *Proc. Telecommun. Energy Conf.*, 2000, pp. 726–732.

[20] K. Chang-Gyun, S. Dong-Hyun, Y. Jung-Sik, P. Jong-Hu, and B. H. Cho, "Design of a contactless battery charger for cellular phone," *IEEE Trans. Ind. Electron.*, vol. 48, no. 6, pp. 1238–1247, Dec. 2001.

[21] H. Abe, H. Sakamoto, and K. Harada, "A noncontact charger using a resonant converter with parallel capacitor of the secondary coil," *IEEE Trans. Ind. Appl.*, vol. 36, no. 2, pp. 444–451, Mar./Apr. 2000.

[22] T. Bieler, M. Perrottet, V. Nguyen, and Y. Perriard, "Contactless power and information transmission," *IEEE Trans. Ind. Appl.*, vol. 38, no. 5, pp. 1266–1272, Sep./Oct. 2002.

[23] A. P. Hu and S. Hussmann, "Improved power flow control for contactless moving sensor applications," *IEEE Power Electron. Lett.*, vol. 2, no. 4, pp. 135–138, Dec. 2004.

[24] T. Hata and T. Ohmae, "Position detection method using induced voltage for battery charge on autonomous electric power supply system for vehicles," in *Proc. 8th IEEE Int. Workshop Adv. Motion Control*, 2004, pp. 187–191.

[25] B. Choi, J. Nho, H. Cha, T. Ahn, and S. Choi, "Design and implementation of low-profile contactless battery charger using planar printed circuit board windings as energy transfer device," *IEEE Trans. Ind. Electron.*, vol. 51, no. 1, pp. 140–147, Feb. 2004.

[26] S. Y. R. Hui and W. C. Ho, "A new generation of universal contactless battery charging platform for portable consumer electronic equipment," *IEEE Trans. Power Electron.*, vol. 20, no. 3, pp. 620–627, May 2005.

[27] J. Gao, "Inductive power transmission for untethered micro-robots," in *Proc. 32nd Annu. Conf. IEEE Ind. Electron. Soc.*, 2005, pp. 2011–2016.

[28] F. F. A. Van der Pijl, J. A. Ferreira, P. Bauer, and H. Polinder, "Design of an inductive contactless power system for multiple users," in *Conf. Rec. Ind. Appl. Conf./41st IAS Annu. Meeting*, 2006, pp. 1876–1883.

[29] X. Liu and S. Y. R. Hui, "Simulation study and experimental verification of a universal contactless battery charging platform with localized charging features," *IEEE Trans. Power Electron.*, vol. 22, no. 6, pp. 2202–2210, Nov. 2007.

[30] U. K. Madawala, D. J. Thimawithana, and N. Kularatna, "An ICPT-supercapacitor hybrid system for surge-free power transfer," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3287–3297, Dec. 2007.

[31] X. Liu and S. Y. R. Hui, "Optimal design of a hybrid winding structure for planar contactless battery charging platform," *IEEE Trans. Power Electron.*, vol. 23, no. 1, pp. 455–463, Jan. 2008.

[32] Z. N. Low, R. A. Chinga, R. Tseng, and J. Lin, "Design and test of a high-power high-efficiency loosely coupled planar wireless power transfer system," *IEEE Trans. Ind. Electron.*, vol. 56, no. 5, pp. 1801–1812, May 2009.

[33] J. J. Casanova, Z. N. Low, and J. Lin, "A loosely coupled planar wireless power system for multiple receivers," *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 3060–3068, Aug. 2009.

[34] W. X. Zhong, L. Xun, and S. Y. R. Hui, "A novel single layer winding array and receiver coil structure for contactless battery charging systems with free-positioning and localized charging features," *IEEE Trans. Ind. Electron.*, vol. 58, no. 9, pp. 4136–4144, Sep. 2011.

[35] G. B. Joung and B. H. Cho, "An energy transmission system for an artificial heart using leakage inductance compensation of transcutaneous transformer," *IEEE Trans. Power Electron.*, vol. 13, no. 6, pp. 1013–1022, Nov. 1998.

[36] W. Guoxing, L. Wentai, M. Sivaprakasam, and G. A. Kendir, "Design and analysis of an adaptive transcutaneous power telemetry for biomedical implants," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 52, no. 10, pp. 2109–2117, Oct. 2005.

[37] G. Wang, W. Liu, M. Sivaprakasam, and G. A. Kendir, "Design and analysis of an adaptive transcutaneous power telemetry for biomedical implants," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 52, no. 10, pp. 2109–2117, Oct. 2005.

[38] P. Si, A. P. Hu, J. W. Hsu, M. Chiang, Y. Wang, S. Malpas, and D. Budgett, "Wireless power supply for implantable biomedical device based on primary input voltage regulation," in *Proc. 2nd IEEE Conf. Ind. Electron. Appl.*, 2007, pp. 235–239.

[39] P. Si, A. P. Hu, S. Malpas, and D. Budgett, "A frequency control method for regulating wireless power to implantable devices," *IEEE Trans. Biomed. Circuits Syst.*, vol. 2, no. 1, pp. 22–29, Mar. 2008.

[40] B. J. Heeres, D. W. Novotny, D. M. Divan, and R. D. Lorenz, "Contactless underwater power delivery," in *Proc. IEEE Power Electron. Specialists Conf.*, 1994, vol. 1, pp. 418–423.

[41] K. W. Klontz, D. M. Divan, D. W. Novotny, and R. D. Lorenz, "Contactless power delivery system for mining applications," *IEEE Trans. Ind. Appl.*, vol. 31, no. 1, pp. 27–35, Jan./Feb. 1995.

[42] B.-M. Song, R. Kratz, and S. Gurol, "Contactless inductive power pickup system for Maglev applications," in *Proc. IEEE 37th Ind. Appl. Conf.*, 2002, pp. 1586–1591.

[43] J. Jia, W. Liu, and H. Wang, "Contactless power delivery system for the underground flat transit of mining," in *Proc. 6th Int. Conf. Electr. Mach. Syst.*, Beijing, China, 2003, pp. 282–284.

[44] T. Kojiya, F. Sato, H. Matsuki, and T. Sato, "Construction of non-contacting power feeding system to underwater vehicle utilizing electromagnetic induction," in *Proc. OCEANS Conf.—Europe*, 2005, pp. 709–712.

[45] H. H. Wu, M. Z. Feng, J. T. Boys, and G. A. Covic, "A wireless multi-drop IPT security camera system," in *Proc. 4th IEEE Conf. Ind. Electron. Appl.*, Xian,, China, May 25–27, 2009, pp. 70–75.

[46] G. A. J. Elliott, J. T. Boys, and A. W. Green, "Magnetically coupled systems for power transfer to electric vehicles," in *Proc. Int. Conf. Power Electron. Drive Syst.*, Singapore, 1995, pp. 797–801.

[47] F. Sato, J. Murakami, T. Suzuki, H. Matsuki, S. Kikuchi, K. Harakawa, H. Osada, and K. Seki, "Contactless energy transmission to mobile loads by CLPS-test driving of an EV with starter batteries," *IEEE Trans. Magn.*, vol. 33, no. 5, pp. 4203–4205, Sep. 1997.

[48] F. Sato, H. Matsuki, S. Kikuchi, T. Seto, T. Satoh, H. Osada, and K. Seki, "A new meander type contactless power transmission system-active excitation with a characteristics of coil shape," *IEEE Trans. Magn.*, vol. 34, no. 4, pp. 2069–2071, Jul. 1998.

[49] G. A. Covic, J. T. Boys, M. L. G. Kissin, and H. G. Lu, "A three-phase inductive power transfer system for roadway-powered vehicles," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3370–3378, Dec. 2007.

[50] M. L. G. Kissin, J. T. Boys, and G. A. Covic, "Interphase mutual inductance in poly-phase inductive power transfer systems," *IEEE Trans. Ind. Electron.*, vol. 56, no. 7, pp. 2393–2400, Jul. 2009.

[51] M. L. G. Kissin, G. A. Covic, and J. T. Boys, "Steady-state flat pickup loading effects in poly-phase inductive power transfer systems," *IEEE Trans. Ind. Electron.*, vol. 58, no. 6, pp. 2274–2282, May 2011.

[52] J. Gao, "Travelling magnetic field for homogeneous wireless power transmission," *IEEE. Trans. Power Delivery*, vol. 22, no. 1, pp. 507–514, Jan. 2007.

[53] G. A. J. Elliott, S. Raabe, G. A. Covic, and J. T. Boys, "Multi-phase pick-ups for large lateral tolerance contactless power transfer systems," *IEEE Trans. Ind. Electron.*, vol. 57, no. 5, pp. 1590–1598, May 2010.

[54] S. Raabe and G. A. Covic, "Practical pick-ups for large lateral tolerance contactless power transfer systems," *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 400–409, Jan. 2013, DOI: 10.1109/TIE.2011.2165461.

[55] A. Zaheer, M. Budhia, K. Kacprzak, and G. A. Covic, "Magnetic design of a 300 W under-floor contactless power transfer system," in *Proc. 37th Annu. Conf. IEEE Ind. Electron. Soc.*, Melbourne, Australia, Nov. 7–10, 2011, pp. 1343–1348.

[56] K. W. Klontz, A. Esser, R. R. Bacon, D. M. Divan, D. W. Novotny, and R. D. Lorenz, "An electric vehicle charging system with 'universal' inductive interface," in *Proc. Power Conv. Conf.*, Yokohama, Japan, 1993, pp. 227–232.

[57] K. W. Klontz, D. M. Divan, and D. W. Novotny, "An actively cooled 120 kW coaxial winding transformer for fast charging electric vehicles," *IEEE Trans. Ind. Appl.*, vol. 31, no. 6, pp. 1257–1263, Nov./Dec. 1995.

[58] R. Severns, E. Yeow, G. Woody, J. Hall, and J. Hayes, "An ultra-compact transformer for a 100 W to 120 kW inductive coupler for electric vehicle battery charging," in *Proc. 11th Annu. Appl. Power Electron. Conf. Expo.*, 1996, pp. 32–38.

[59] R. Laouamer, M. Brunello, J. P. Ferrieux, O. Normand, and N. Buchheit, "A multi-resonant converter for non-contact charging with electromagnetic coupling," in *Proc. 23rd Int. Conf. Ind. Electron. Control Instrum.*, 1997, vol. 2, pp. 792–797.

[60] J. G. Hayes, M. G. Egan, J. M. D. Murphy, S. E. Schulz, and J. T. Hall, "Wide-load-range resonant converter supplying the SAE J-1773 electric vehicle inductive charging interface," *IEEE Trans. Ind. Appl.*, vol. 35, no. 4, pp. 884–895, Jul.–Aug. 1999.

[61] H. Sakamoto, K. Harada, S. Washimiya, K. Takehara, Y. Matsuo, and F. Nakao, "Large air-gap coupler for inductive charger [for electric vehicles]," *IEEE Trans. Magn.*, vol. 35, no. 5, pp. 3526–3528, Sep. 1999.

[62] M. G. Egan, D. L. O'Sullivan, J. G. Hayes, M. J. Willers, and C. P. Henze, "Power-factor-corrected single stage inductive charger for electric vehicle batteries," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 1217–1226, Apr. 2007.

[63] A. Esser, "Contactless charging and communications for electric vehicles," *IEEE Ind. Appl. Mag.*, vol. 1, no. 6, pp. 4–11, Nov./Dec. 1995.

[64] J. Hirai, K. Tae-Woong, and A. Kawamura, "Study on intelligent battery charging using inductive transmission of power and information," *IEEE Trans. Power Electron.*, vol. 15, no. 2, pp. 335–345, Mar. 2000.

[65] Y. Matsuo, O. M. Kondoh, and F. Nakao, "Controlling new die mechanisms for magnetic characteristics of super-large ferrite cores," *IEEE Trans. Magn.*, vol. 36, no. 5, pp. 3411–3414, Sep. 2000.

[66] G. A. Covic, G. Elliott, O. H. Stielau, R. M. Green, and J. T. Boys, "The design of a contact-less energy transfer system for a

people mover system," in *Proc. Int. Conf. Power Syst. Technol.*, Dec. 2000, vol. 1, pp. 79–84.

[67] F. Nakao, Y. Matsuo, M. Kitaoka, and H. Sakamoto, "Ferrite core couplers for inductive chargers," in *Proc. Power Conv. Conf.*, Osaka, Japan, 2002, vol. 2, pp. 850–854.

[68] R. Macke and C. Rathge, "High frequency resonant inverter for contactless energy transmission over large air-gap," in *Proc. 35th Annu. Power Electron. Specialist Conf.*, Aachen, Germany, 2004, pp. 1737–1743.

[69] C. S. Wang, O. H. Stielau, and G. A. Covic, "Design considerations for a contactless electric vehicle battery charger," *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1308–1314, Oct. 2005.

[70] Y. Matsuda, H. Sakamoto, H. Shibuya, and S. Murata, "A non-contact energy transferring system for an electric vehicle-charging system based on recycled products," *J. Appl. Phys.*, vol. 99, pp. 08R902–08R903, Apr. 2006.

[71] V. V. Haerri and D. Martinovic, "Supercapacitor module SAM for hybrid busses: An advanced energy storage specification based on experiences with the TOHYCO-rider bus project," in *Proc. IEEE IES 33rd Annu. Conf.*, 2007, pp. 268–273.

[72] Y. Kamiya, M. Nakaoka, T. Sato, J. Kusaka, Y. Daisho, S. Takahashi, and K. Narusawa, "Development and performance evaluation of advanced electric micro bus equipped with non-contact inductive rapid-charging system," in *Proc. 23rd Int. Electric Veh. Symp.*, Anaheim, CA, USA, 2007, DOI: 10.1109/VPPC.2011.6042979.

[73] S. Judek and K. Karwowski, "Supply of electric vehicles via magnetically coupled air coils," in *Proc. 13th Power Electron. Motion Control Conf.*, 2008, pp. 1497–1504.

[74] M. Dockhorn, D. Kurschner, and R. Mecke, "Contactless power transmission with new secondary converter topology," in *Proc. 13th Power Electron. Motion Control Conf.*, 2008, pp. 1734–1739.

[75] J. L. Villa, J. Sallán, A. Llombart, and J. F. Sanz, "Design of a high frequency inductively coupled power transfer system for electric vehicle battery charge," *Appl. Energy*, vol. 86, no. 3, pp. 355–363, 2009.

[76] S. Valtchev, B. Borges, K. Brandisky, and J. B. Klaassens, "Resonant contactless energy transfer with improved efficiency," *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 685–699, Mar. 2009.

[77] J. Sallen, J. L. Villa, A. Llombart, and J. F. Sanz, "Optimal design of ICPT systems applied to electric vehicle battery charge," *IEEE. Trans. Ind. Electron.*, vol. 56, no. 6, pp. 2140–2149, Jun. 2009.

[78] C.-Y. Huang, J. T. Boys, G. A. Covic, and M. Budhia, "Practical considerations for designing IPT system for EV battery charging," in *Proc. IEEE Veh. Power Propul. Conf.*, Sep. 7–11, 2009, pp. 402–407.

[79] V. V. Haerri, U. K. Madawala, D. J. Thrimawithana, R. Arnold, and A. Maksimovic, "A plug in hybrid 'Blue Angel III' for vehicle to grid system with a wireless grid interface," in *Proc. IEEE Veh. Power Propul. Conf.*, 2010, DOI: 10.1109/VPPC.2010.5729148.

[80] A. J. Moradewicz and M. P. Kazmierkowski, "Contactless energy transfer system with FPGA-controlled resonant converter," *IEEE Trans. Ind. Electron.*, vol. 59, no. 2, pp. 945–951, Sep. 2010.

[81] M. Budhia, G. A. Covic, and J. T. Boys, "Design and optimisation of magnetic structures for lumped inductive power transfer systems," *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3096–3108, Nov. 2011.

[82] Y. Nagatsuka, N. Ehara, Y. Kaneko, S. Abe, and T. Yasuda, "Compact contactless power transfer system for electric vehicles," in *Proc. Int. Power Electron. Conf.*, Sapporo, Japan, Jun. 21–24, 2010, pp. 807–813.

[83] M. Budhia, G. A. Covic, and J. T. Boys, "A new magnetic coupler for inductive power transfer electric vehicle charging systems," in *Proc. 36th Annu. Conf. IEEE Ind. Electron. Soc.*, Phoenix, AZ, USA, Nov. 7–10, 2010, pp. 2487–2492.

[84] Y. Nagatsuka, S. Noguchi, Y. Kaneko, S. Abe, T. Yasuda, K. Ida, A. Suzuki, and R. Yamanouchi, "Contactless power transfer system for electric vehicle battery charger," in *Proc. 25th World Battery Hybrid Fuel Cell Symp. Exhibit.*, Shenzhen, China, 2010, pp. 1–6.

[85] M. Budhia, J. T. Boys, G. A. Covic, and C.-Y. Huang, "Development of a single-sided flux magnetic coupler for electric vehicle IPT charging systems," *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 318–328, Jan. 2013, DOI: 10.1109/TIE.2011.2179274.

[86] G. A. Covic, L. G. Kissin, D. Kacprzak, N. Clausen, and H. Hao, "A bipolar primary pad topology for EV stationary charging and highway power by inductive coupling," in *Proc. IEEE Energy Conv. Congr. Expo.*, Phoenix, AZ, USA, Sep. 17–22, 2011, pp. 1832–1838.

[87] M. Chigira, Y. Nagatsuka, Y. Kaneko, S. Abe, T. Yasuda, and A. Suzuki, "Small-size light-weight transformer with new core structure for contactless electric vehicle power transfer system," in *Proc. IEEE Energy Conv. Congr. Expo.*, Phoenix, AZ, USA, Sep. 17–22, 2011, pp. 260–266.

[88] M. Budhia, G. A. Covic, J. T. Boys, and C.-Y. Huang, "Development and evaluation of single sided flux couplers for contactless electric vehicle charging," in *Proc. IEEE Energy Conv. Congr. Expo.*, Phoenix, AZ, USA, Sep. 17–22, 2011, pp. 614–621.

[89] J. G. Bolger, F. A. Kirsten, and L. S. Ng, "Inductive power coupling for an electric highway system," in *Proc. IEEE 28th Veh. Technol. Conf.*, Mar. 1978, vol. 28, pp. 137–144.

[90] C. E. Zell and J. G. Bolger, "Development of an engineering prototype of a roadway powered electric transit vehicle system," in *Proc. 32nd IEEE Veh. Technol. Conf.*, May 1982, vol. 32, pp. 435–438.

[91] K. Lashkari, S. E. Shladover, and E. H. Lechner, "Inductive power transfer to an electric vehicle," in *Proc 8th Int. Electr. Veh. Symp.*, 1986, pp. 258–267.

[92] J. G. Bolger, "Urban electric transportation systems: The role of magnetic power transfer," in *Conf. Rec. WESCON. "Idea/Microelectronics"*, 1994, pp. 41–45.

[93] M. Eghtesadi, "Inductive power transfer to an electric vehicle-analytical model," in *Proc. IEEE 40th Veh. Technol. Conf.*, 1990, pp. 100–104.

[94] H. R. Ross, E. H. Lechner, and R. N. Schweinberg, "Play a vista roadway powered electric vehicle project," in *Proc. Int. Electr. Veh. Symp.*, Hong Kong, 1990, vol. 10, pp. 981–992.

[95] "Roadway powered electric vehicle project track construction and testing program phase 3D," Systems Control Technology, Inc., Palo Alto, CA, USA, California PATH research paper UCB-ITS-PRR-94-07, 10551425, Mar. 1994.

[96] Z. Pantic, B. Sanzhong, and S. M. Lukic, "Inductively coupled power transfer for continuously powered electric vehicles," in *Proc. IEEE Veh. Power Propul. Conf.*, 2009, pp. 1271–1278.

[97] A. Brooker, M. Thornton, and J. Rugh, "Technology improvement pathways to cost effective vehicle electrification," in *Proc. SAE 2010 World Congr.*, Detroit, MI, USA, Apr. 13–15, 2010, pp. 1–15.

[98] G. A. Covic, J. T. Boys, M. Budhia, and C.-Y. Huang, "Electric vehicles—Personal transportation for the future," in *Proc. 25th World Battery Hybrid Fuel Cell Electr. Veh. Symp. Expo.*, Shenzhen, China, Nov. 5–9, 2010, pp. 1–10.

[99] S. W. Lee, J. Huh, C. B. Park, N. S. Choi, G.-H. Cho, and C.-T. Rim, "On-line electric vehicle using inductive power transfer system," in *Proc. IEEE Energy Conv. Congr. Expo.*, Atlanta, GA, USA, Sep. 12–16, 2010, pp. 1598–1601.

[100] S. Ahn and J. Kim, "Magnetic field design for high efficient and low EMF wireless power transfer in on-line electric vehicle," in *Proc. EuCAP*, Rome, Italy, Apr. 11–15, 2011, pp. 3979–3982.

[101] J. Huh, S. W. Lee, W. Y. Lee, G. H. Cho, and C.-T. Rim, "Narrow-width inductive power transfer system for on-line electrical vehicles," *IEEE Trans. Power Electron.*, vol. 26, no. 12, pp. 3666–3679, Dec. 2011.

[102] A. W. Green, "Modelling a push-pull parallel resonant convertor using generalized state space averaging," *Inst. Electr. Eng. Proc. B*, vol. 140, no. 6, pp. 350–356, Nov. 1993.

[103] O. H. Stielau and G. A. Covic, "Design of loosely coupled inductive power transfer systems," in *Proc. IEEE Power Syst. Technol. Conf.*, 2000, vol. 1, pp. 85–90.

[104] S. Dieckerhoff, M. J. Ruan, and R. W. De Doncker, "Design of an IGBT-based LCL-resonant inverter for high-frequency induction heating," in *Proc. IEEE Ind. Appl. Conf.*, 1999, vol. 3, pp. 2039–2045.

[105] C. S. Wang, G. A. Covic, and O. H. Stielau, "Investigating an LCL load resonant inverter for inductive power transfer applications," *IEEE Trans. Power Electron.*, vol. 19, no. 4, pp. 995–1002, Jul. 2004.

[106] J. Meins, F. Turki, and R. Czainski, "Contactless high power supply," in *Proc. Unconv. Electromech. Electr. Syst.*, Alushta, Ukraine, 2004, pp. 581–586.

[107] J. Meins, F. Turki, and R. Czainski, "Phase control of resonant power supply inverters," in *Proc. Eur. Conf. Power Electron. Appl.*, Dresden, Germany, 2005, pp. 1–7.

[108] M. Borage, S. Tiwari, and S. Kotaiah, "Analysis and design of an LCL-T resonant converter as a constant-current power supply," *IEEE Trans. Ind. Electron.*, vol. 52, no. 6, pp. 1547–1554, Dec. 2005.

[109] M. Borage, S. Tiwari, and S. Kotaiah, "LCL-T resonant converter with clamp diodes: A novel constant-current power supply with inherent constant-voltage limit," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 741–746, Apr. 2007.

[110] M. Borage, K. V. Nagesh, M. S. Bhatia, and S. Tiwari, "Design of LCL-T resonant converter includeing the effect of transformer winding capacitance," *IEEE Trans. Ind. Electron.*, vol. 56, no. 5, pp. 1420–1427, May 2009.

[111] J. T. Boys, C.-Y. Huang, and G. A. Covic, "Single phase unity power-factor IPT system," in *Proc. 34th Annu. IEEE Power Electron. Specialists Conf.*, 2008, pp. 3701–3706.

[112] M. L. G. Kissin, C. Y. Huang, G. A. Covic, and J. T. Boys, "Detection of the tuned point of a fixed-frequency LCL resonant power supply," *IEEE Trans. Power Electron.*, vol. 24, no. 4, pp. 1140–1143, Apr. 2009.

[113] H. Hao, G. A. Covic, M. L. G. Kissin, and J. T. Boys, "A parallel topology for inductive power transfer power supplies," in *Proc. Appl. Power Electron. Conf. Expo.*, Fort Worth, TX, USA, Mar. 6–10, 2011, pp. 2027–2034.

[114] H. L. Li, A. P. Hu, and G. A. Covic, "A direct AC-AC converter for inductive power transfer systems," *IEEE Trans. Power Electron.*, vol. 27, no. 2, pp. 661–668, May 2012.

[115] J. T. Boys, G. A. Covic, and Y. Xu, "DC analysis technique for inductive power transfer pick-ups," *IEEE Power Electron. Lett.*, vol. 1, no. 2, pp. 51–53, Jun. 2003.

[116] P. Si and A. P. Hu, "Analyses of DC inductance used in ICPT power pick-ups for maximum power transfer," in *Proc. IEEE PES Transmiss. Distrib. Conf. Exhib.*, 2005, DOI: 10.1109/TDC.2005.1546918.

[117] G. A. Covic, J. E. James, and J. T. Boys, "Analysis of a series tuned ICPT pick-up using DC transformer modelling methods," in *Proc. 6th Int. Power Eng. Conf.*, Singapore, 2003, pp. 51–56.

[118] I. C. Chan, G. A. Covic, and J. T. Boys, "Regulator capacitor selection for series compensated IPT pickups," in *Proc. 34th Annu. Conf. IEEE Ind. Electron.*, 2008, pp. 932–937.

[119] N. A. Keeling, G. A. Covic, and J. T. Boys, "A unity power factor IPT pick-up for high power applications," *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 744–751, Feb. 2010.

[120] C.-Y. Huang, J. T. Boys, G. A. Covic, and S. Ren, "LCL pick-up circulating current controller for IPT systems," in *Proc. IEEE Energy Conv. Conf. Expo.*, Atlanta, GA, USA, Sep. 12–16, 2010, pp. 640–646.

[121] C.-S. Wang, G. A. Covic, and O. H. Stielau, "General stability criterions for zero phase angle controlled loosely coupled inductive power transfer systems," in *Proc. IEEE Ind. Electron. Conf.*, 2001, vol. 2, pp. 1049–1054.

[122] C.-S. Wang, G. A. Covic, and O. H. Stielau, "Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer systems," *IEEE Trans. Ind. Electron.*, vol. 51, no. 1, pp. 148–157, Feb. 2004.

[123] Y. H. Chao, J. J. Shieh, C.-T. Pan, W.-C. Shen, and M.-P. Chen, "A primary-side control strategy for series-parallel loosely coupled inductive power transfer systems," in *Proc. IEEE Conf. Ind. Electron. Appl.*, 2007, pp. 2322–2327.

[124] X. Liu, W. M. Ng, C. K. Lee, and S. Y. Hui, "Optimal operation of contactless transformers with resonance in secondary circuits," in *Proc 23rd Annu. IEEE Appl. Power Electron. Conf.*, Austin, TX, USA, Feb. 24–28, 2008, pp. 645–650.

[125] J. U. W. Hsu, A. P. Hu, and A. Swain, "A wireless power pickup based on directional tuning control of magnetic amplifier," *IEEE Trans. Ind. Electron.*, vol. 56, no. 7, pp. 2771–2781, Jul. 2009.

[126] J. U. Hsu, A. P. Hu, P. Si, and A. Swain, "Power flow control of a 3-D wireless power pick-up," in *Proc. IEEE Conf. Ind. Electron. Appl.*, Harbin, China, 2007, pp. 2172–2177.

[127] G. A. Covic, J. T. Boys, A. M. W. Tam, and J. C.-H. Peng, "Self tuning pick-ups for inductive power transfer," in *Proc. 34th Annu. IEEE Power Electron. Specialists Conf.*, 2008, pp. 3486–3494.

[128] N. A. Keeling, G. A. Covic, J. T. Boys, H. Hao, and L. George, "Variable tuning in LCL compensated contactless power transfer pickups," in *Proc. Inaugural IEEE Energy Conv. Conf. Expo.*, San Jose, CA, USA, Sep. 20–24, 2009, pp. 1826–1832.

[129] International Commission on Non-Ionizing Radiation Protection," Guidelines for limiting exposure to time-varying electric and magnetic, fields (1 Hz to 100 kHz)," *Health Phys.*, vol. 99, no. 6, pp. 818–836, Dec. 2010.

[130] International Commission on Non-Ionizing Radiation Protection, "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 Ghz)," *Health Phys.*, vol. 74, pp. 494–592, 1998.

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