

Multiphase Pickups for Large Lateral Tolerance Contactless Power-Transfer Systems

Grant A. J. Elliott, Stefan Raabe, *Student Member, IEEE*, Grant A. Covic, *Senior Member, IEEE*, and John T. Boys

Abstract—The majority of commercial contactless power-transfer systems used in manufacturing applications can only tolerate limited movement of the power pickup relative to the track to which it is magnetically coupled. This paper describes a new multiphase (quadrature) pickup that significantly improves the tolerance of the power receiver to such relative movement, enabling expanded applications such as continuously powered automatic guided vehicles, robots, and other vehicles to be considered. The advantage gained is largely independent of the track type, so that single-phase or multiphase tracks can be used as desired to improve both the power transfer and lateral tolerance as required. The improvement is achieved by capturing both vertical and horizontal components of magnetic flux around any track.

Index Terms—Contactless power transfer, magnetically coupled systems.

I. INTRODUCTION

INDUCTIVE (contactless) power-transfer (IPT) systems utilize the magnetic field around a current-carrying wire at very low frequencies (VLFs) to wirelessly couple power to one or more secondary systems at good efficiency [1]. The noncontact nature of the system enables many advantages to be realized; the electronics can be completely sealed so that they produce no residues, they are unaffected by the environment, and they have proven to be robust in operation and are inherently safe due to the natural isolation of the system. Many commercial applications exist today that take advantage of these features, particularly where the cost benefits can be easily quantified. Such applications include clean-room systems, material-handling monorail-based systems (often automotive assembly) when the environment is extremely dirty, slow-moving automatic guided vehicles (AGVs) with track-following navigation, and battery-charging systems. These systems are designed to transfer power continuously, provided that good horizontal and vertical alignment exists between the track and power pickups. This requirement is easily met in monorail systems, where the pickup is naturally constrained by the bogey, which has led to many commercial systems [1], [2], and in stationary battery-charging systems relying on user plug-in or position alignment to enable electric vehicles [3]–[8].

Commercial systems that allow some freedom of movement relative to the track are more difficult to realize, but many applications where this would be beneficial include robots, AGVs, and people movers, where having highly constrained movement relative to a buried track is limiting. Batteries, or some other storage means can be carried to alleviate this problem, but, ideally, such storage should be limited and not depleted while the vehicle is in the proximity of the track.

While roadway-vehicle applications using IPT have been proposed for more than two decades [9]–[11], there has been a limited commercial development due to the need to constrain the vehicle movement to ensure adequate power transfer. Systems that have been commercialized rely on automatic steering control [12], and the tolerance required by actual systems is such that human operators cannot meet them. To overcome this, compromises such as oversized or multiple pickups must be used to compensate for any misalignment [13]. Alternatively, the track can be modified to cater for misalignment. 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 [14], [15]. These systems usually require some form of on-board storage to manage fluctuations and facilitate starting [10]–[12], [15]. Recently, polyphase track configurations have been employed to compensate for misalignment by producing a traveling magnetic wave [16], [17]. 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 system is well designed while providing significant lateral tolerance.

This paper focuses on the means by which standard flat pickups (used commercially in AGV and moving-vehicle systems) can be improved to increase the vehicle tolerance to lateral movement irrespective of the chosen track configuration. Two new pickup coil designs are described that enable improved magnetic coupling without the need to modify the magnetic shape of the chosen pickup. The proposed designs can be applied to most practical industrial pickups and the additional power-processing circuitry is minimal. This paper begins by presenting the principles of IPT and the movement limitations on existing IPT systems. Following this, the proposed pickup designs are presented along with suitable controllers. This paper investigates the impact on selected single-phase tracks, meander tracks, and multiphase tracks to show the practicality of the approach.

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G. A. J. Elliott was with The University of Auckland, Auckland 1142, New Zealand. He is now with LUMIDIEM Corporation, Dubai, United Arab Emirates (e-mail: grant.elliott.nz@gmail.com).

S. Raabe, G. A. Covic, and J. T. Boys are with the Department of Electrical and Computer Engineering, The University of Auckland, Auckland 1142, New Zealand (e-mail: sraa001@aucklanduni.ac.nz; ga.covic@auckland.ac.nz; j.boys@auckland.ac.nz).

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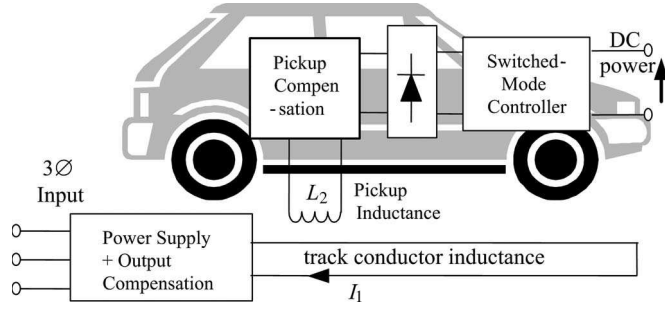


Fig. 1. Typical IPT system.

II. PRINCIPLES OF IPT

IPT systems consist of three main components: a power supply, a track, and a pickup, as shown in Fig. 1. The power supply is used to energize the elongated loop (track) with a constant current, at VLFs (typically 10–40 kHz). Pickups placed in proximity to the track couple power magnetically into the power receiver. The coupled receiving coil is compensated (tuned at the frequency of the track) and the ac power is then rectified and regulated to dc to supply the drive motors and other loads.

As shown, in its most basic form, an IPT pickup consists of a coil of wire 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 a 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 IPT pickups is primarily determined from two parameters [1]: the open-circuit voltage induced in the pickup coil at frequency (ω) due to the primary track current (I_1), $V_{oc} = j\omega MI_1$, and the short circuit current, $I_{sc} = MI_1/L_2$, which is the maximum current from V_{oc} limited by the impedance of the pickup coil L_2 . Here, M is the mutual inductance between the track and the pickup coil.

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

$$S_u = V_{oc} I_{sc} = \omega \frac{M^2}{L_2} I_1^2. \quad (1)$$

However, without compensation, the maximum power that can be drawn from a pickup is $S_u/2$. To improve the power available to the pickup, the pickup inductor is compensated with capacitors such that it resonates at the frequency of the track. The output power into a load is thereby improved by $2Q$ resulting in

$$P = Q \cdot S_u = Q \cdot V_{oc} \cdot I_{sc} = Q \cdot \omega \frac{M^2}{L_2} I_1^2. \quad (2)$$

Here, Q is the tuned quality factor, which is determined by the output load or controller by controlling the output voltage/current [1]. Practical factors such as VA ratings, component tolerances, and aging affect the sensitivity and power transfer of the circuit for high values of Q , which is normally designed to be less than ten for all practical operating conditions. Other

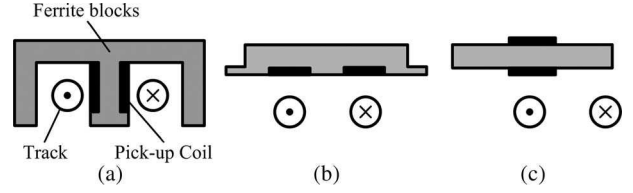


Fig. 2. Common IPT pickups. (a) E-pick-up. (b) Flat-E. (c) Flat pickup.

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 the semiconductor devices used in the power supply and the Litz wire used in the track and magnetic components. The remaining factors affecting power relate to the magnetic design of the pickup.

As previously mentioned, magnetic material such as ferrite is used to improve the coupling and, hence, power transfer between the track and the pickups. In IPT systems where the primary drives an extended loop (as discussed here), the cost of placing ferrite in the track is normally prohibitive. As such, all of the ferrite exists in the secondary, and this design is carefully optimized to increase the coupling factor M/L_2 [18]. The magnetic design of pickups for moving vehicles is limited by the application. Fig. 2(a) shows a common pickup shape for material-handling systems where the pickup is placed on a bogie moving along a fixed monorail. Here, 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. On the other hand, AGVs, robots, and other forms of vehicular systems commonly move on and above surfaces/roadways which must allow freedom of movement for all vehicle types. Consequently, the track is usually buried, and the pickup designs are normally flat as shown in Fig. 2(b) and (c).

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. 2(b) and (c) are optimized to capture either the vertical [Fig. 2(b)] or horizontal [Fig. 2(c)] component of the 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 [18], but it is very sensitive to any misalignment. The horizontal pickup has a power null that exists at the center of the track and maxima which ideally exist directly above each conductor, and these maxima, while not as large (given the field from only one conductor is being captured), are less sensitive to lateral movement.

III. QUADRATURE PICKUP

The limitation on lateral movement in traditional pickups has been the power nulls present in both horizontal and vertical flux

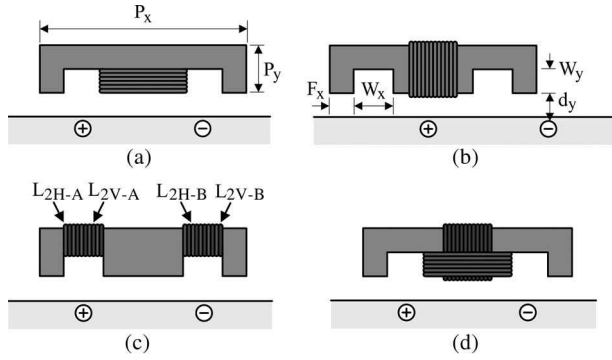


Fig. 3. (a) Flat-E pickup. (b) Flat pickup wound on a Flat-E core. (c) Quadrature pickup design one. (d) Quadrature pickup design two.

TABLE I
PICKUP DIMENSIONS [SHOWN IN FIG. 3(a) AND (b)]

	Symbols	Dimension (mm)
Pick-up Height	P_y	20
Pick-up Width	P_x	144
Pick-up Length	P_z	200
Gap	d_y	30
Ferrite foot width	F_x	10
Winding area height	W_y	10
Winding area width	W_x	31

pickups as previously described. By noting that the minima and maxima in a standard Flat-E vertical flux [Fig. 2(b)] pickup and the flat-bar horizontal pickup [Fig. 2(c)] are complementary, a new pickup design can be created that utilizes both coils to capture the vertical and horizontal components of the field.

In order to investigate this possibility, a small-scale prototype was constructed using industry-standard ferrite pieces used for a Flat-E in the configuration shown in the cross section of Fig. 3(a). Dimensions shown include the distance from the track cables to the base of the ferrite (d_y), the pickup height in the y -direction (P_y), and width in the x -direction (P_x) of the pickup and various inner dimensions. Values for these are given in Table I. In a commercial design, the pickup length (P_z), while not shown, is in the direction of the track conductors and can be extended to increase the open circuit voltage and, consequently, to improve S_u as required, while the design of the cross section influences the short-circuit current [18]. No attempt here is made to modify the ferrite; rather, a second coil can be added as shown separately in Fig. 3(b) to enable the horizontal flux to be captured from the track. When the outputs from both coils are combined, the null points that exist in the individual power profiles should be eliminated enabling a much-improved tolerance to horizontal misalignment from the ideal pickup position.

Two potential design solutions using this approach are shown in Fig. 3(c) and (d), while their operation is described more specifically in the sections which follow. In both cases, the configuration of these coils is such that they are forced to capture quadrature components of the flux vector. Consequently, these pickups are termed quadrature pickups [19]. Furthermore, provided the coils operate only on quadrature flux components, there will be no mutual coupling between them, and, hence, the coils are completely independent, allowing indepen-

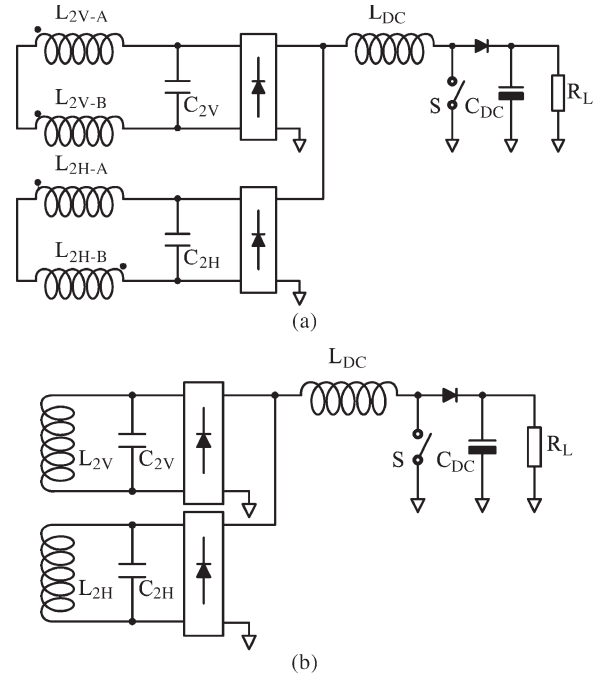


Fig. 4. Quadrature pickup controllers for (a) design one and (b) design two.

dent tuning or short circuiting under power control without affecting each other.

Fig. 4 shows suitable controllers for both quadrature pickup designs comprising vertical and horizontal coils or coil pairs, labeled L_{2V} and L_{2H} , respectively. The horizontal and vertical coils operate independently and, therefore, can be independently tuned. Either series or parallel tuning can be used to boost the power by Q as described in (2). However, parallel tuning is often preferred as shown in Fig. 4 because this naturally produces a current limit, meaning that only voltage control is required, but, more importantly, because of the impact that these vehicles have on the track and supply as explained next. After tuning, each output is rectified before being summed and controlled using a standard current-sourced “boost” decoupling controller used in many IPT systems [1], [20].

In vehicular systems, there may be an unknown number of vehicles on the track at any one time. The supply sees both the reflected impedance from the secondary that must be driven and a change in the primary inductance of the track due to the presence of the pickup ferrite. Ideally, any change to the reactive impedance seen by the supply should be minimized as this affects the reactive VAs which must be supplied, and, if significant, will impact the VA rating of the supply. In parallel-tuned systems, the reflected impedance of a secondary circuit (Z_r) as seen by the primary under perfect or near-perfect tuning conditions (such that $\omega = \omega_o = 1/\sqrt{L_2 C_2}$) is given by [21]

$$Z_{ro} = Z_r(\omega = \omega_o) = \frac{M^2}{L_2^2} (R - j\omega_o L_2). \quad (3)$$

Here, R is the equivalent load across the secondary-tuned circuit which combines the actual load R_L , the action of the rectifier, and the controlling switch.

The parallel-tuned circuit presents both a real and reactive load back onto the track, the magnitude of which is affected

by the coupling. The reactive component partially cancels any increase in inductance of the track due to the presence of the pickup ferrite, so that there is little variation in the track inductance as the number of vehicles coupled to the track varies. Series-tuned systems, on the other hand, reflect only a resistive load on the primary, and, consequently, the track inductance will vary as more vehicles are added to and removed from the track.

A. Design and Test Procedure

To test and compare the effectiveness of both quadrature-pickup designs, two small-scale prototypes were constructed using the parameters of Table I (as described earlier). Each coil shown was wound with 16 turns using a light hookup wire (0.3 mm² conductor, 1.2-mm diameter including insulation). Both prototype pickups were then evaluated under simulation and experimental conditions by taking V_{oc} and I_{sc} measurements at a constant height of 20 mm above a track after which S_u was determined from (1). In all cases, the track-conductor separation was set at 93-mm spacing, and the primary current was set to a modest 10-A rms at 38.4 kHz. The primary-track cable was 6-mm² Litz wire.

Numerous simulations were then performed using a finite-element magnetic modeling package called JMAG. The pickup was evaluated as it was shifted at constant height by laterally moving it at 10-mm intervals from the center of the track-conductor cables.

To verify the S_u profiles from simulation, experimental measurements were taken at 10-mm intervals on an experimental rig operating under identical conditions. The results, as discussed in following sections, show good correlation. This enabled various other design options to be quickly verified, some of which could not easily have been evaluated practically due to limitations in time, cost, and availability of ferrite to set up each experimental system.

The experimental control circuits shown in Fig. 4 were also constructed for each quadrature pickup to determine the maximum power able to be extracted. In this evaluation, the regulator was designed to control the output voltage at 10 V. Each winding's power capability was then evaluated separately (by disconnecting either the horizontal or vertical winding, in turn) and finally evaluated with both connected. The dc output resistance was varied until the maximum power at 10 V was determined, and this was noted at each position. For the pickup size under investigation, the distance from the track and the track currents used, power levels of around 1 W can be expected. Clearly, 1 W is not a very practical power level for a commercial application. AGVs, etc., typically require continuous power on the order of 500 W–2 kW during operation. In a commercial system, the pickup lengths are typically five times greater than that used here, resulting in an increase in V_{oc} and S_u of ~five times for a given track current. Furthermore, track currents on the order of 100–200 A are typical. Consequently, if a pickup with five times the length were employed in a system with 100-A track current, the output power of such a practical system using (2) would be more than 500 times greater and 2000 times greater at 200 A. Consequently, the impact of this

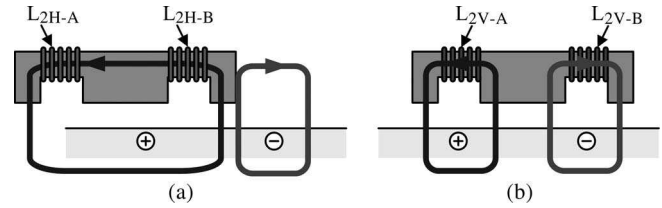


Fig. 5. Quadrature pickup design one with lateral offset where: (a) in-phase windings produce maximum power and (b) out-of-phase windings produce maximum power.

work can be readily evaluated for such practical systems using simple scale factors.

B. Evaluation of Quadrature Design One

The first quadrature pickup design of Fig. 3(c) was wound with two windings on each half of the pickup core (a total of four windings) with both coils L_{2H-A} and L_{2V-A} interleaved. The same interleaving was undertaken for L_{2H-B} and L_{2V-B} . This winding approach was considered because it can easily be applied to either the flat-E pickup of Fig. 2(b) or the simple flat pickup of Fig. 2(c). In this design, one pair of the windings (L_{2H-A} and L_{2H-B}) are connected in phase, while the other pair (L_{2V-A} and L_{2V-B}) are connected out of phase. Each pair of coils has a total of 16 turns between them, wound in a single layer. The in-phase coils capture the horizontal flux and, hence, should capture maximum power when located above one of the track conductors [Fig. 5(a)]. Likewise, the out of phase coils capture the vertical flux and are at maximum output when located centrally between the two track conductors, as shown in Fig. 5(b). These pairs of windings are used with the controller of Fig. 4(a) to provide the necessary power to the load.

For the pickup structure shown, each coil takes up half the winding area, and there is no reduction in clearance between the pickup and the track so long as the coils do not extend below the ferrite. The return path of each coil winding does, however, sit above the pickup structure which would need to be considered during manufacture.

As shown in Fig. 6(a), the measured and simulated results of S_u are in good agreement, and, as expected, the power nulls are removed and the lateral tolerance is significantly improved. Interestingly, the maxima in the horizontal power profile do not occur at the minima of the vertical profile (which, for the evaluated system, should be around 45–50 mm on either side of the track center) as expected. Instead the horizontal maxima occur much further out (around ± 80 mm) when the inner horizontal coil is positioned close to or above a track conductor. This exacerbates the peaks and troughs of the S_u profile and needs to be considered in any design, perhaps, by reshaping the ferrite to enable suitable coil repositioning while ensuring good coupling. In Fig. 6(b), power is shown to be available over a much-improved range, compared with the pickup with only a vertical winding. Again, the peaks and troughs are exaggerated due to the S_u profile indicating that further optimization work is required to balance the power from both the horizontal and vertical coils.

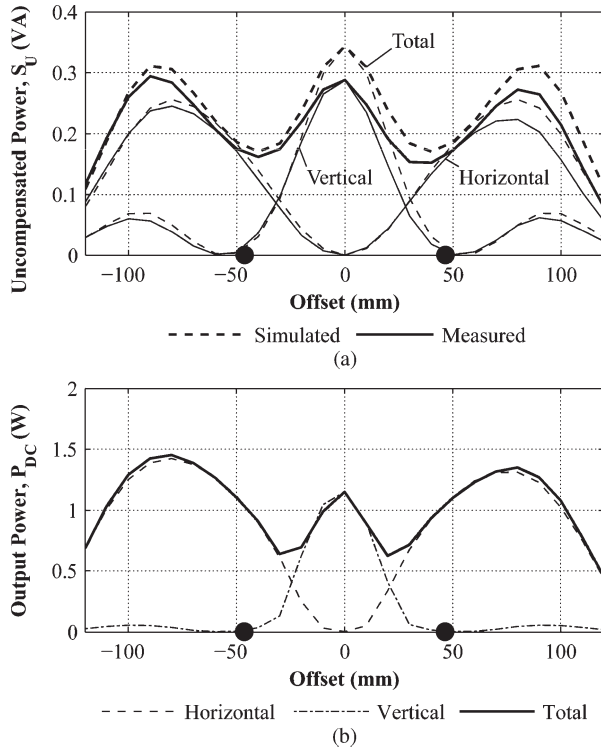


Fig. 6. Quadrature pickup design one: (a) Simulated and measured results of uncompensated power. (b) Measured results of output dc power.

C. Evaluation of Quadrature Design Two

The second quadrature pickup design of Fig. 3(d) uses only two coils and is based on commercial flat-E pickups which are designed specifically to capture only the vertical field. In this design, the vertical coil is unchanged (two layers of eight turns each for this design), while a second coil (designed to capture the horizontal flux component) is simply prefabricated to fit in the center. Under manufacture, this can simply be slid over the ferrite before inserting the vertical coil. Both coils are essentially wound around the center of the ferrite and orientated to capture the horizontal and the vertical components of the magnetic field. A disadvantage of this design (as shown) is that this second horizontal coil must necessarily extend beyond the ferrite, so that the clearance between the pickup and the track is reduced by the thickness of the coil, in this case, one winding layer. This needs to be considered in any practical design, particularly if the ground clearance must be fixed.

The measured and simulated results shown in Fig. 7(a) are again in good agreement. Because the coils are both centered around the pickup structure, the maxima and minima are coincident resulting in an output which not only greatly improves the lateral tolerance but also has a very smooth S_u profile.

The contribution of each of the coils to the dc output power is shown in Fig. 7(b). In practice, the power results are somewhat different from the S_u profiles because the operating Q of each coil is not the same and varies with offset. The actual operating Q 's are only constrained by the output regulator which, in this design, simply controls the voltage to the load. In practice, the controller could be modified to control the power, or separate regulators could be employed, if desired, to exert greater control over each coil's contribution.

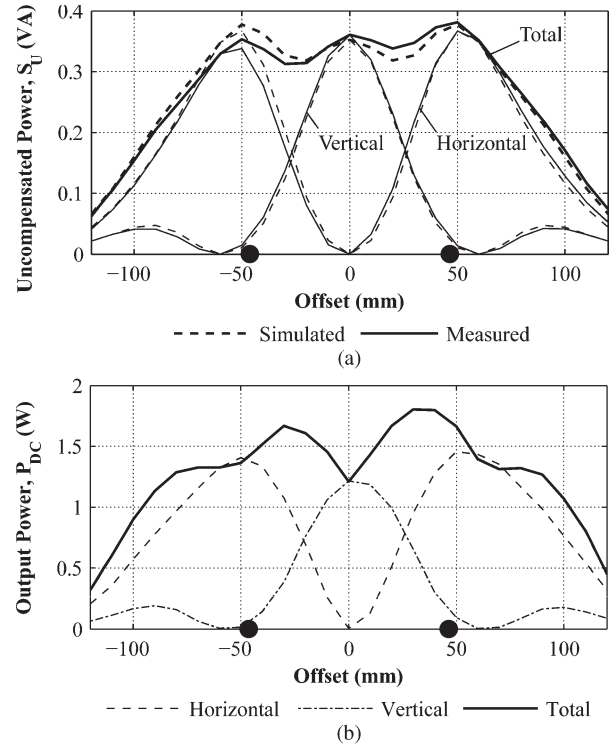


Fig. 7. Quadrature pickup design two: (a) Simulated and measured results of uncompensated power. (b) Measured results of output dc power.

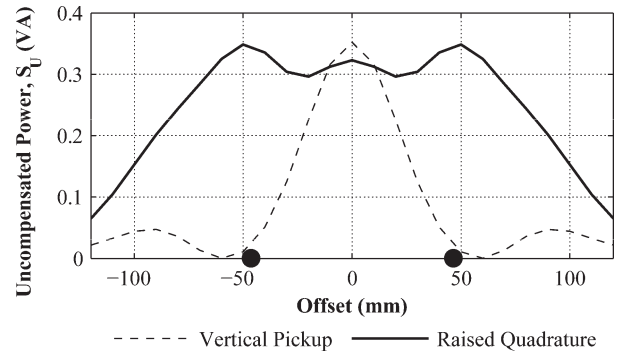


Fig. 8. Simulated results for the quadrature pickup design two showing the total power of the pickup when it is raised by the coil height versus its uncompensated vertical power unraised.

For a desired output power of 1 W, it can be seen that the vertical winding alone has a lateral tolerance of approximately ± 15 mm. Thus, in order to ensure power transfer, an AGV system is required to operate within a tolerance of ± 10 mm. With the combined output of both quadrature coils, the pickup can easily produce this power over a tolerance of ± 100 mm, an improvement of 660% for this particular track layout.

In order to quantify the effect of reduced clearance between the pickup and the track, the results of Fig. 7(a) were both simulated and remeasured after first raising the pickup by the thickness of the horizontal coil (around 1.5 mm in the example). In practice, this corresponds to a height increase of around 8%. The results of this investigation are shown in Fig. 8.

Notably, for the vertical component, there is a reduction in uncompensated power around the maximum point with the corresponding reduction in M . The horizontal coupling is largely

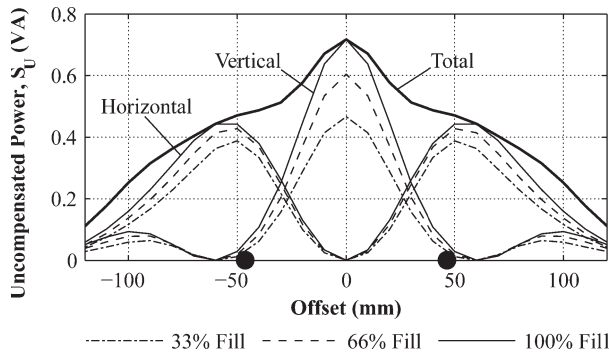


Fig. 9. Evaluation of increasing coil width to optimize field capture showing horizontal and vertical S_u field components starting with the unoptimized winding results in Fig. 7(b) and increasing until maximum fill is obtained. Total power available using both coils with 100% fill is also shown.

unaffected. In consequence, the available power at the center is reduced by as much as 25%, but the lateral tolerance remains high. This power reduction needs to be considered in practical designs and may require some compensation or redesign of the pickup shape. Due to the smooth power profile of design two over design one, it is deemed the preferable design.

D. Further Practical Aspects of Quadrature Pickups

Commercial pickups almost always fill the winding area as this helps to minimize leakage and enhance coupling between the track and the pickup. This also maximizes the copper cross-sectional area, reducing winding losses. In the aforementioned work, only a portion of the winding area was filled in order to have identical turns for both windings. Fig. 9 shows the impact of using all of the available winding area for both the vertical and horizontal components. Here, the width of the horizontal winding is limited by the size of ferrite (61 mm) in the center of the pickup shown in Fig. 3(b). Both the horizontal and vertical S_u components are shown to improve compared with the results of Fig. 7(a), although the vertical component has a more significant improvement, given that as the winding area is filled, the average coil width increases from around 62 to 93 mm, enabling a greater area for flux capture.

In consequence, one of the difficulties is to both maximize and balance the uncompensated power output from each of the quadrature coils so that they produce similar levels of voltage and current at their respective maxima. This is due to the fact that the cross-sectional area and coupling of each coil to the track is quite different. Magnetic design or electronic-tuning methods can be used to improve each coil's power profile and shape the maximum power that can be obtained with variations in horizontal displacement. Additionally, the magnitude of the vertical-flux component, and, hence, the total power output, will be affected by the track spacing as will be shown later. Unfortunately, a detailed analysis of all such behavior is not possible here. Rather, as stated earlier, the focus of this paper is to show the improvements a quadrature coil can add to a typical industrial IPT pickup when coupled with various practical and proposed track configurations, without reengineering the complete pickup structure. As such, the following section describes improvements that might be expected from using a quadrature

pickup if it were applied to repeated single-phase bipolar or three-phase configurations as previously proposed for vehicular systems in the literature.

IV. THREE-PHASE AND REPEATED SINGLE-PHASE BIPOLAR TRACKS

To further increase the lateral tolerance of the pickup, suitable track configurations such as repeated single-phase bipolar tracks or meander configurations [14], [15], or a polyphase tracks [16] have been proposed. In a previous work, multiple pickups have been placed under a vehicle to overcome the inherent nulls in a meander or repeated single-phase bipolar configuration. This is unnecessary if the tracks can be spaced suitably to ensure a consistent power profile over as wide an area as desired. Multiphase track configurations, on the other hand, create a moving magnetic field around the track conductors. This field contains both vertical and horizontal field components, and the simple horizontal pickups as proposed in Fig. 2(c) can be used to capture just the time-varying horizontal component of the field. While no nulls appear in the power profile, some improvement should be possible if the instantaneous components of both fields are captured.

The effectiveness of using the quadrature pickup (design two with parameters as described in Table I and 100% fill for all windings as in Fig. 9) on both types of tracks was investigated and compared. The majority of such evaluations were undertaken by simulation given that earlier measurement and simulation results have proven to be extremely close. Selected experimental results are also included for the three-phase track system verifying the accuracy of the predictions. The first system tested uses three repeated bipolar tracks (each having identical spacing between track conductors and identical track currents synchronized in phase), while the second system uses a three-phase bipolar configuration [16] with identical track currents to that of the single-phase system, except with a 60° phase displacement between adjacent cables. The track current chosen for all evaluations is 40 A/phase.

Various track spacing was investigated for both systems. For the repeated single phase system 80, 100, 120, and 140 mm spacing are shown, as these values are similar to those commonly used in industrial applications for which the chosen pickup shape is designed. The three-phase track system is similarly investigated with the track spacing set to 40 (matching a similar track setup to that of [16]), 80, and 100 mm spacing.

Fig. 10(a) shows the combined S_u profile using the three repeated single-phase tracks at 80-mm track spacing. While the results show the effectiveness of the quadrature pickup to couple power across a wide power zone, it is clear that the pickup is too wide for the track spacing shown, so that in the center of the track, there is some negative coupling from a nearby track causing a diminished power transfer. This negative coupling is eliminated near the edges allowing higher powers to be transferred. Notably, the track current is four times greater than that investigated in Section III, so that if but one track were present, an S_u profile with peaks that are 16 times larger (around 5–6 VA) than that of Fig. 7(a) would be expected. As shown near the edges, this power is even higher by as much as

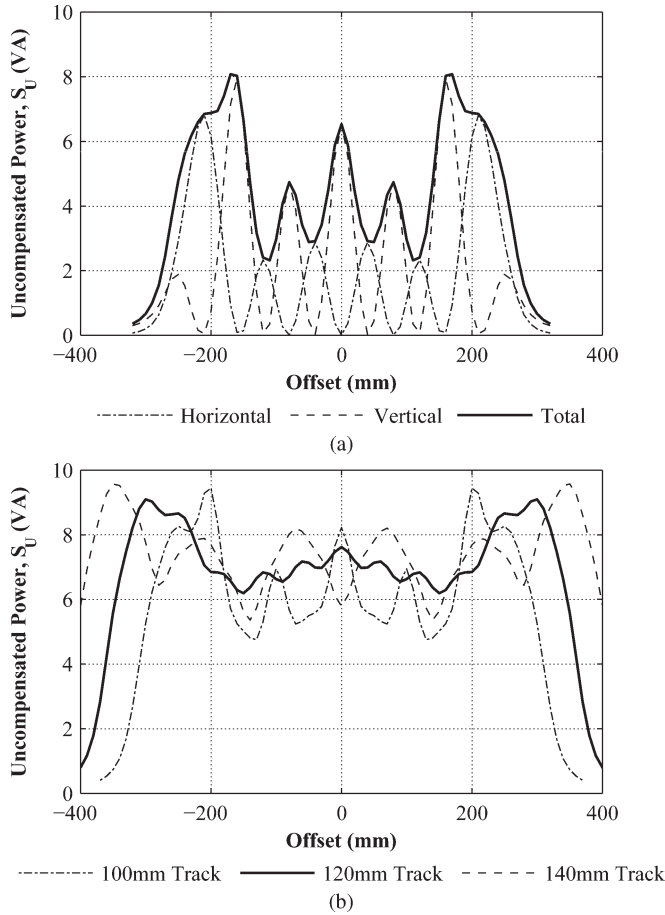


Fig. 10. VA profiles with the (design two) quadrature pickup on a three-single phase bipolar track system with the various track spacings: (a) 80 mm spacing showing vertical, horizontal, and total S_u . (b) 100 mm, 120 mm, and 140 mm track spacings showing just the total S_u .

25% on average indicating some constructive coupling at the edges. When wider track spacing is used as shown in the total power profiles of Fig. 10(b), the negative coupling is largely mitigated, and the power profile is vastly improved. As shown for 100 mm, the dips in the profile are much reduced and the peak power of both the vertical and horizontal components increase substantially. With 120-mm track spacing, this result is further improved, while for 140 mm, the system becomes less optimal as the percentage of vertical field component drops away. Further increases in track spacing significantly degrade the overall performance.

Thus, for any system, careful design is necessary to optimize the track separations together with the magnetic pickup structure and the position of the horizontal and vertical coils to ensure a smooth power delivery. Once determined, the lateral tolerance of a system can continue to be improved by adding more track wires, although track losses and cost will place practical limits on all such systems.

The effectiveness of the quadrature pickup with a three-phase track structure having a 40-mm track spacing between conductors (as proposed in [16]) is shown in Fig. 11. In this system, both coils of the quadrature pickup are wound using 16 turns of 1.2 mm diameter Litz as described in Section III-A, which is much less than the available winding area. Both measured

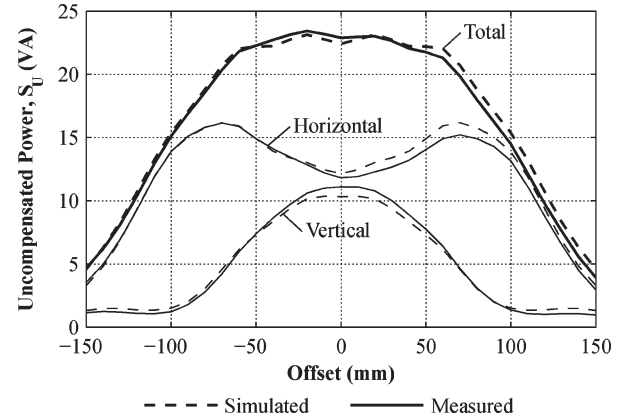


Fig. 11. Experimental and simulated results of the unoptimized quadrature pickup (design two) on a three-phase bipolar track with 40 mm spacing.

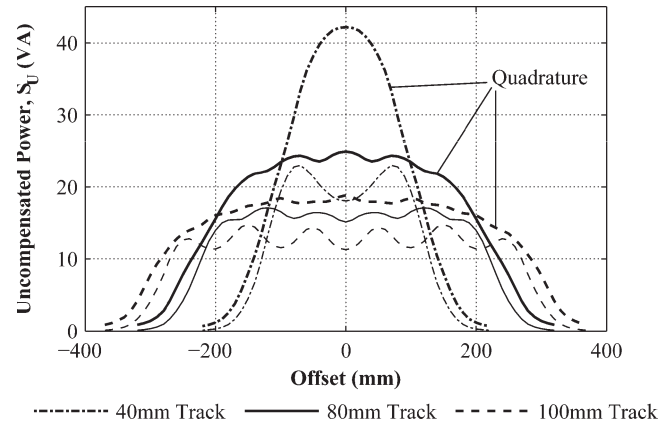


Fig. 12. Quadrature pickup (design two) on a three-phase bipolar track with 40 mm, 80 mm, and 100 mm track spacing. Total quadrature S_u is labeled, while the horizontal component for the flat-E pickup shown for comparison is not.

and simulated results show excellent agreement. In this track configuration, the phase wires are separated by 120 mm, and here, the captured vertical and horizontal flux components are well matched (similar to that found with the repeated single-phase tracks of Fig. 10) resulting in significant improvements in the total S_u profile.

Given the proven accuracy of the simulation, the quadrature pickup with 100% winding fill (as described in Section III-D) was investigated under simulation, using a similar three-phase track structure but with varying spacing between conductors. The results of these simulations are shown in Fig. 12 and compare the combined quadrature S_u profile against using only a horizontal coil S_u profile as originally proposed in [16]. Notably, the available power for the quadrature pickup with 100% fill has almost doubled the available power in the center compared with the result of Fig. 11 and has more than doubled the output compared with that achieved if only a horizontally wound coil were used (as in [16]) for around 70% of the lateral tolerance. With the track-conductor spacing set to 80 mm (each phase spaced 240 mm apart), the quadrature power output remains higher than that achieved using 40 mm spacing with just a horizontal coil, while extending the lateral tolerance by almost 200%. The power profile is also flatter. However, the contribution of the vertical component to the overall performance

is not as high, given the larger phase spacing. At 100-mm track conductor spacing, the improvements provided by the quadrature coil are not as significant, although the output power is still greater and flatter meaning that the output regulator would not have to work as hard to deliver the required power to the load and would be more tolerant to variations.

Thus, the quadrature pickup shows clear improvements in a three-phase track system, increasing either power or lateral tolerance (or both) and smoothing the power profile. This increase in effectiveness comes at a fairly small cost in terms of an extra coil and tuning required in the pickup.

Comparing the results of the repeated single-phase and the three-phase bipolar system at any given track spacing, it is clear that the latter would be preferred. While both achieve similar horizontal tolerance, the output power of the three-phase system is always significantly better due to the manner in which power is coupled from nearby tracks. In both cases, the balance between the vertical and horizontal component is best achieved when the vertical winding is spaced with a gap similar to the spacing between the wires of any one phase.

V. CONCLUSION

Two new multiphase (quadrature) pickups have been presented that capture both vertical and horizontal components of the magnetic field around any IPT track. As shown, they allow greater lateral movement and more consistent power delivery. In single-phase track systems, the power nulls are eliminated allowing increased lateral tolerance, although the total power is not increased substantially. There are distinct advantages to using quadrature pickups in both repeated single-phase and three-phase bipolar track systems, although the latter shows more practical promise. In the former, lateral tolerance can be significantly improved with but small improvements in power transfer. In the latter, the resulting power profiles are much smoother and significantly higher while still achieving equally good lateral tolerance.

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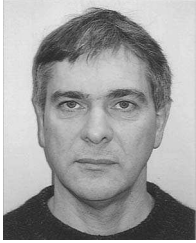
Grant A. J. Elliott received the B.E. Hons. and Ph.D. degrees in electrical and electronic engineering from The University of Auckland, Auckland, New Zealand, in 1994 and 2006, respectively.

He founded LED video company Day One Digital Media in 2000 before returning in 2004 to The University of Auckland to complete his Ph.D. studies. Since completing his studies, he has held Chief Technical Officer (CTO) positions with several leading LED video companies globally. He is currently CTO of LUMIDIEM Corporation headquartered in Dubai, and based in Hong Kong. His current interests include LED lighting display technology and inductive (contactless) power transfer.



Stefan Raabe (S'04) received the B.E. Hons. degree in electrical and electronic engineering from The University of Auckland, Auckland, New Zealand, in 2006, where he is currently working toward the Ph.D. degree.

His research interests include inductive (contactless) power transfer systems.



Grant A. Covic (S'88–M'89–SM'04) received the B.E. Hons. and Ph.D. degrees from The University of Auckland, Auckland, New Zealand, in 1986 and 1993, respectively.

He is with The University of Auckland where he was appointed as a full-time Lecturer in 1992 in the Department of Electrical and Computer Engineering, a Senior lecturer in 2000, and an Associate Professor in 2007, and where currently, he and Prof. J. T. Boys jointly head the power-research cluster in the faculty of engineering. He has published

more than 80 papers in international journals and conference proceedings and is the holder of a number of patents in the field of inductive (contactless) power transfer (IPT). His current research and consulting interests include power electronics and IPT.



John T. Boys received the Ph.D. degree from The University of Auckland, Auckland, New Zealand, in 1962.

After completing his Ph.D. studies, he was with SPS Technologies for five years before returning to academia as a Lecturer at the University of Canterbury, Christchurch, New Zealand. He moved to Auckland in 1977 where he developed his work in power electronics. He is currently a Professor of electronics at The University of Auckland, where he is active in teaching and research in the Department of Electrical and Computer Engineering. He has published more than

100 papers in international journals and is the holder of more than 20 U.S. patents from which licenses in specialized application areas have been granted around the world. His specialist research areas are power electronics and inductive power transfer where he and Prof. G. A. Covic jointly head a research group.

Prof. Boys is a Fellow of the Royal Society of New Zealand and a Distinguished Fellow of the Institution of Professional Engineers New Zealand.