Magnetic Design of a Three-Phase Inductive Power Transfer System for Roadway Powered Electric Vehicles

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***Abstract*-Inductive Power Transfer (IPT) is a viable method for recharging and powering Electric Vehicles (EV) along a roadway since it is safe, efficient and convenient. This is however, a demanding application because power needs to be transferred over relatively large air gaps of 150-200mm while allowing sufficient horizontal tolerance across the width of the lane, to enable an unguided vehicle to receive full power. The design of the power track is critical to large scale implementation, to ensure that losses and cost are minimised while maximising horizontal tolerance. The approach used in this paper overcomes the limitations of earlier track designs and allows designers to increase horizontal tolerance with minimal cost, enabling an EV roadway system to be considered in future. A 2.5m long track is built for lab testing and compared to a 3D finite element model, after which, the design is refined via simulation to meet the tolerance and power requirements of an EV.**

I. INTRODUCTION

Electric vehicles (EV) help reduce dependence on fossil fuels, emission of greenhouse gasses and emission of pollutants. Consequently, uptake of EVs has been increasing since the 1990's however market penetration has been low because EVs are not as cost effective as conventional vehicles. The present EV market is dominated by hybrid vehicles that derive their energy from a combustion engine, however, plug-in EVs (PHEV) have recently been introduced enabling energy from the grid to mitigate gasoline consumption. In order for EVs to gain widespread adoption, major improvements are required in battery life and cost, and grid connection. The latter allows opportunistic charging after each trip rather than a long charge at the end of the day. As a result battery wear is significantly reduced by minimising the depth of discharge and the EV has a lower cost since a smaller battery is required [1-3]. The preferred solution, that makes EVs more cost effective than gasoline vehicles, as discussed in [2], is to power and recharge the EV via the road. It should be noted that the infrastructure for such a dynamic charging system could be relatively small because travel on interstate highways makes up 1% of roadway miles but carries 22% of all vehicle miles travelled. An EV that has 50% of its driven miles connected to a dynamic charging system would be as cost effective as a conventional vehicle and does not incur additional gasoline costs [2, 4].

The purpose of this research is to investigate a practical Inductive Power Transfer (IPT) system capable of powering and recharging EVs on a roadway thereby completely minimising onboard energy storage and hence vehicle weight and cost. IPT is based on Ampere's and Faraday's Laws and uses a varying magnetic field to couple power across an air gap, to a load, without physical contact. System performance is not affected by wet or dirty environments and there are no safety risks under such conditions since the components are completely isolated. IPT is reliable and maintenance free unlike conventional plug or brush and bar contact based methods such as those used on trams and electric buses [5]. IPT is presently used in numerous industrial applications such as materials handling and IC fabrication. The systems vary in capacity from 1W–200kW and can be used to both power and recharge robots, Automatic Guided Vehicles (AGV), electronic devices [6], recreational people movers [7], buses and EVs [8]. IPT systems may be divided into two distinct types: distributed systems that consist of one or more movable loads that may be placed anywhere on a track, and lumped systems that only allow power transfer at a defined location.

Distributed systems are particularly suited to Roadway Powered EV (RPEV) applications, however practical large scale RPEV systems have so far been infeasible. This is due to the large horizontal (~700mm) tolerance and ground clearance (150-200mm) required by unguided EVs. The track topology presented in this paper offers a significant improvement over previous designs by allowing increased horizontal tolerance with minimal increase to the system cost.

This paper is structured as follows; the concepts of an IPT system are explained followed by a comparison between conventional track systems and the new topology. A small scale laboratory prototype track is built to test the new track and compare results with those from a finite element simulation model. Subsequently, a simulation approach is used to design a practical system that is able to meet the power and tolerance requirements on an EV.

II. IPT CONCEPTS

An IPT system comprises three main components that are shown for a single phase system in Fig. 1. The power supply produces a sinusoidal current in the 10-40 kHz frequency range that drives a current (I_1) in an inductive track. The parallel compensation capacitor C_1 allows the track current, , to resonate increasing the magnetic field strength in the vicinity of the track, this minimises the VA rating of the power supply for a given load [5]. The track and Pick Up (PU) act as a loosely coupled transformer enabling power transfer over relatively large air gaps. The IPT PU inductance, L_2, is tuned for resonance with C_2, this compensates for the relatively large PU leakage inductance. The voltage across C_2

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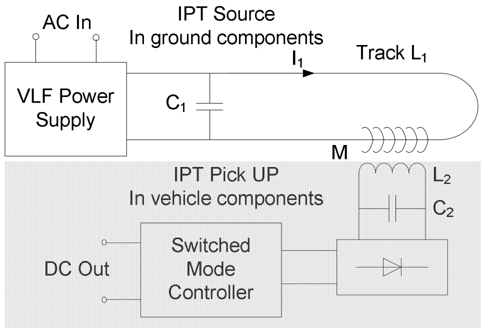

Fig. 1. IPT system components for a single phase track system.

is rectified and a switched mode controller enables the resonant tank to operate at a defined quality factor, Q, to boost power transfer and provide a usable DC output. The power output of an IPT system (P_{out}) is quantified by the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) of the PU as well as the quality factor as shown in (1).

$$P_{out} = P_{su} * Q = V_{oc} * I_{sc} * Q = \omega M I_1 * \frac{M I_1}{L_2} * Q = \omega I_1^2 \frac{M^2}{L_2} Q \qquad (1)$$

P_{su} is the uncompensated power, ω is the angular frequency of the track current I_1, M is the mutual inductance between the track and PU. As shown in (1), the output power is dependent on the power supply (ωI_1^2), magnetic coupling (M^2/L_2) and PU controller (Q). Increasing the power output and separation between the track and PU is highly desirable but efficiency is limited by the operational frequency (switching loss) and current rating (copper loss) of the system. Allowing a system to operate at a high Q boosts power transfer but in practical applications it is normally designed to operate between 4 and 6 due to component VA ratings and tolerances [5]. Due to these limits, the greatest increase in system performance can be achieved by good magnetic design.

III. ROADWAY IPT TRACKS

A. Single Phase Systems

A laboratory 16kW prototype single phase RPEV system has been built in the past. The track was essentially an elongated spiral winding with the longer sides placed on adjacent lanes. Consequently the PU is only exposed to flux generated by current flowing in one direction and there are no nulls in the power profile across the track as would occur with a simple PU on a conventional single phase track, where the conductors are placed side by side [9]. The system was built before modern ferrites and power electronic components were developed, and this is reflected in its performance. The air gap between the track and PU was controlled by an electronic actuator to be 30mm and full power could be supplied up to an offset of 120mm from the track centre. The relatively low horizontal tolerance necessitated an automatic guidance system [10].

A 5kW single phase system that operates with a 200mm air gap has been built and tested in [11], however the horizontal tolerance is 60mm. Notably, the system does not use ferrite in the PU and this causes significant problems when installed in an EV. Ferrite ensures the flux remains within the PU and allows aluminium shielding to be used, this is necessary to limit losses in the steel chassis and to meet magnetic field exposure guidelines [12].

The approach employed in [13] to improve the horizontal tolerance on a single phase track was to use a complicated PU that contained six offset coils. As the PU is moved horizontally across the track different sets of coils are energised thus increasing tolerance. However this approach is not suitable for high power systems due to mutual coupling between the coils that makes tuning the active coil problematic. The unused parallel tuned coils need to be shorted and doing so affects the flux path of the active coil resulting in losses.

B. Bipolar Three Phase Systems

In order to improve horizontal tolerance, a three phase track topology as shown in Fig.2 (a) was proposed in [9], the vehicle drives along the length of the track, Tx, which is referred to as the x-axis. The system uses an inductor-capacitor-inductor (LCL) impedance converting network that converts the voltage sourced inverter into a current source suitable for driving the inductive track. The leakage inductance of the isolating transformer is used as the first inductor and the track forms the last inductor, so that only real power passes through the transformer. Large reactive currents (I_1 in Fig.1) circulate in the track and capacitor only. Three individual isolating transformers connected in a delta-delta configuration were used for each phase, however the output terminals of the transformers were connected directly to the start and return of each track loop resulting in a six wire track. This track topology is termed bipolar because the PU is exposed to both forward and returning currents to the supply. The overlapping nature of the track phases results in currents that differ by 60° in each adjacent wire and in a similar manner to windings in a cage induction motor, this creates a travelling field across the width (Ty) of the track. This moving field results in a wide and even power profile with a simple single coil PU.

However, a consequence of having overlapping tracks is the presence of mutual inductance between phases, so that energy from one track phase couples into adjacent phases, similar to the power coupling between each track conductor and the PU. This cross coupling causes different legs in the inverter to source large currents and the DC bus voltage surges as energy is fed into the inverter. Two approaches were shown to solve the mutual inductance problem. Firstly the

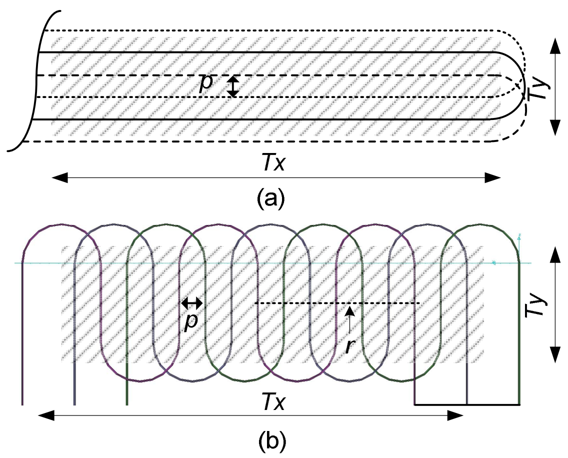

Fig. 2. Three phase track topologies (a) bipolar and (b) unipolar.

area of overlap between track loops can be changed to reduce the mutual inductance- however this results in a non-uniform track spacing that affects the smoothness of the power profile across the width of the track. Secondly, a flux cancelling approach can be used where transformer coupling is introduced at the start of the track to create coupling between phases that is out of phase with the coupling between the tracks along the length due to geometry. This is implemented by appropriately looping the track through toroidal cores at the start. The first technique minimises the effect of interphase mutual inductance but resulted in either poorer performance in the coupled PU, while the second has good performance but added expense due to the extra magnetic components required [14].

C. Unipolar Three Phase Track

The three phase track topology presented in this paper comprises three overlaid conductors that are terminated to a wye point at the end as shown in Fig. 2 (b). Note the pitch of the track, p, is the distance between conductors. This topology is referred to as a unipolar three phase track because there are no explicit return conductors. Although there are only three conductors, the nature of the layout means that the PU is effectively exposed to forward and reverse currents that are 60° apart when defined from a fixed reference direction, r, in Fig. 2(b). The time varying constructive addition of the flux from each conductor results in travelling magnetic pole pairs along the length of the track, Tx. Two of these are shown in Fig. 3, which illustrates the magnetic flux density vectors in a cut plane through section line r. The width of the pole varies between the track pitch and twice the track pitch however the distance from pole centre to centre remains three times the pitch. The unipolar track has two key advantages over the bipolar design, namely balanced interphase coupling and improved horizontal tolerance. Due to the geometry of the track, there is equal coupling between phases and this can easily be accounted for in the LC portion of the impedance converting network. An example of favourable balanced coupling is when energy is coupled to phase B from A at a given position along the track, because the directions of A and B change along the length of the track with respect to a fixed reference, this results in energy coupling to phase A from B and there is no net energy transfer. The power supply used for this track is identical to that of the bipolar track described in [14] however the outputs of the transformers are connected to the track in a wye configuration.

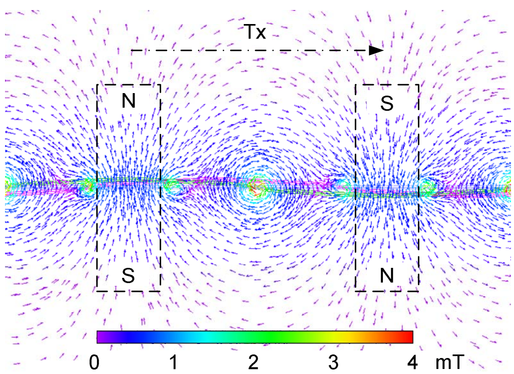

Fig. 3. Magnetic flux density in cross-section through center of a unipolar track with pole positions shown.

With a unipolar track, the horizontal tolerance of a PU is largely decoupled from the resonant current rating of the track and capacitor (C_2 in Fig. 1). The power transfer to a PU of fixed dimensions depends on the pitch or spaces between the track cables. That is, if the pitch of a bipolar track is increased to improve horizontal tolerance, the track current must increase to maintain the same flux density (B) above the track to ensure equivalent power transfer (B is proportional to $1/d^2$). Higher currents result in improved power transfer but also in greater copper loss (I^2R) in the track that reduce efficiency. However, in the unipolar track, the width determines the horizontal tolerance as shown by the shaded area in Fig. 2 (b). Increasing tolerance by making the track wider is preferable because the added length only increases the copper loss linearly.

Wider tracks are more efficient in terms of coupling area for a given track length (Tx) because the length of the curved edges is constant. It may appear that the length of wire required for a given length of unipolar track is greater than that of a bipolar track but that is not the case when the areas of full power transfer are compared. The shaded area, shown in Fig. 2(b), for the bipolar track does not cover the outer conductors because the power transfer drops significantly before the edges of the track. Note the edges of the unipolar track were made circular to simplify the simulation model however straight edges can be used in practice to reduce wire length.

To test the concept of a unipolar track topology, a 2210mmLx890mmW section with a pitch of 65mm was built. The width of the track was determined by the length of the straight midsection, which was 500mm, and the pitch. The central section of the track was made up of 5 periods of each phase, to minimise unbalanced interphase coupling due to end effects. A simple 16 turn flat bar pickup measuring 168mmL x 93mmW x 16mmT was used for testing and comparison with a 3D finite element model. The PU consisted of 6 standard 'I' cores made from N87 material, which has a relative permeability of 2400. The spread of the PU coil was adjusted to cover 80% of the PU length, as this value has been shown to be optimal in [9]. The test track was constructed with stranded mains cable rather than Litz wire for ease of prototyping, as such the maximum current without excessive track heating was 22.5A RMS at 38.4kHz. The V_{oc} and I_{sc} measurements obtained from the model created in JMAG were found to agree within 5% of those measured on average. This enables large models suitable for RPEVs to be investigated and optimised via simulation with confidence.

D. Power Requrements

A power input of 20 - 30kW to an EV is sufficient for motive power and charging while driving in various situations such as urban, highway and mountainous terrains [4, 15]. The energy collected by the EV depends on the length of powered road, and the vehicle speed. As such, powered sections are particularly suited where average vehicle speeds are low. Additionally, the placement of powered sections on steep sections of roadway is desirable as this will limit the discharge rate of the vehicle battery and prolong its life.

Another advantage of the proposed unipolar topology, shown in Fig. 2(b), is that the pattern can be easily continued at either end by adding additional tracks either side. Interleaving enables long sections of road to be continuously powered provided the power supplies are synchronised. It is envisaged that such a track system will be completely modular with power supplies powering fixed lengths of track in the order of 10's of metres. This system is extremely reliable, if one section gets damaged or one power supply fails, the powered roadway will still function.

IV. Track Design

To ensure an RPEV system is as cost effective and efficient as possible, it is critical that the magnetic components are optimal. The following parameters affect the output power of the system: PU length, width, and thickness, track pitch and width, and the design of the ferrite structure under the track. To investigate each variable thoroughly is beyond the scope of this paper. The width of the track is not investigated, it can be widened if more horizontal tolerance is required. There are numerous PU topologies and considering each type is exhaustive and not necessary. Coupling between the track and PU is due to mutual inductance and this is proportional to the area intersected by flux generated by both magnetic components. Consequently, PU topologies that have small areas or volumes are fundamentally not suited to high power large air gap applications where large horizontal tolerance is needed. In this paper, a simple flat bar PU is investigated and the track is optimised. Such a PU will only couple power when the magnetic field is horizontal, illustrated by the flux vectors in Fig. 3. A new PU topology, termed the quadrature, has been proposed in [13]. This PU contains additional coils that are able to take advantage of the vertical field component that simply adds a fixed amount of power to the EV. Therefore if a track is optimised for a simple PU, the track can be considered optimal. The approach used in this paper is to ensure the PU length is matched to the track. Following that, ferrite is added under the track to improve performance.

A. Matching PU Length to Track Pitch

There are two approaches to matching the track pitch and PU length, namely varying the length of the PU with a fixed pitch track or varying the pitch with a fixed PU length. Both techniques have been investigated via simulation (note the track current was 22.5A at 38.4kHz and the air gap was 60mm). The graph in Fig. 4 shows the uncompensated power of the PU as it is made longer on a track with a pitch of 65mm. The coupling is at a maximum when the PU is four times the pitch or 260mm long. This result is consistent with the field vectors shown in Fig. 3. The pole pitch is three times that of the track and with 80% of the ferrite covered, almost all of the available horizontal flux is captured resulting in maximum coupling. Increasing the PU and hence coil length is undesirable as the direction of the horizontal field changes to oppose the flux in the centre of the PU ferrite. In this work, ferrite utilisation efficiency is a metric used to compare designs. It is determined by dividing the P_{su} by the volume of ferrite. Given the width of the PU is constant, this ferrite utilisation can be compared as VA/cm of PU length. Designs that have a PU length 2.8 times the pitch have been found to offer the best coupling for a given volume of ferrite and hence PU weight.

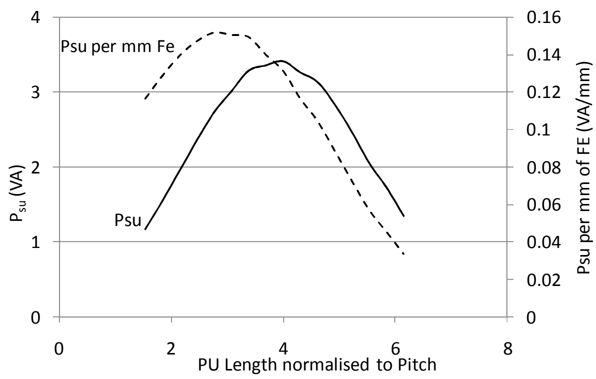

Fig. 4. Normalised P_{su} and power per mm of ferrite for a PU.

The effect of increasing the track pitch for PUs of various lengths is shown in Fig. 5 where the PU lengths have been normalised to the track pitch. The peak in coupled power occurs at PU lengths 2.2 to 2.4 times the track pitch. Clearly, larger PUs and larger pitches permit more power transfer, however this result appears to conflict with the previous simulation results in Fig. 4. The power output of a 260mm long PU on a 120mm pitch track is almost double that of the same PU on a 65mm pitch track. The difference in coupling is due to flux cancellation and the fundamental flux path height above the track. A track that has a pitch of 65mm has almost two poles for an optimal length PU. Therefore this PU will experience more flux cancellation than it would on a track with a 120mm pitch. The PU coupling is at a maximum when the poles are positioned equidistantly from the PU ends and reaches a null when a pole is centred under a PU as shown in Fig. 6 (a) and (b). With a track that has a relatively small pitch compared to the PU length (for example in Fig. 6 (a)), the poles are closer together resulting in more flux cancellation for a given PU length. Increasing the pitch, as shown in Fig. 6 (b), increases the pole pitch, resulting in less cancellation because the distance to the next pole is greater. The fundamental flux height above the track determines how much flux will be coupled to the PU and this height is determined by the pitch of the track. Having a low pitch means the height of the flux path above the track is limited and this is approximated by h in Fig. 6 (a). Note the height is shown under the track for convenience, in practice the flux

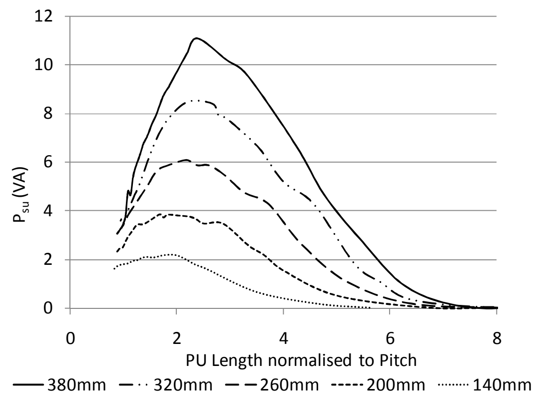

Fig. 5. P_{su} for PUs of various lengths normalised to track pitch

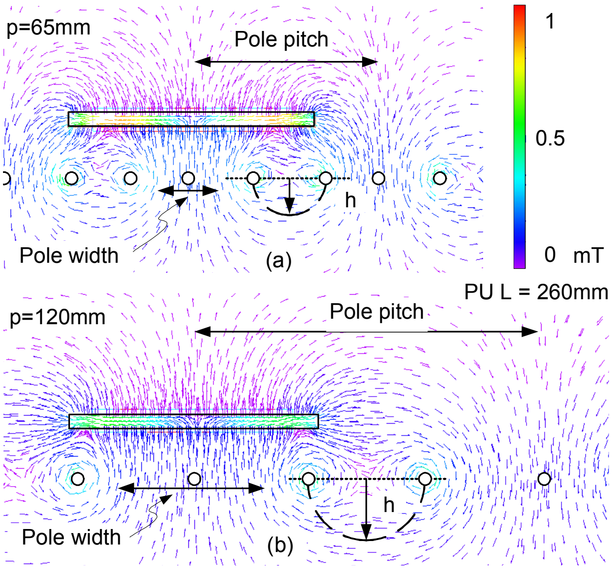

Fig. 6. . Magnetic flux vectors illustrating nulls with optimal PUs on tracks with small and large pitches. The fundamental flux heights are shown by h.

about a track without ferrite is symmetrical. Doubling the pitch doubles the flux path height, as indicated in Fig. 6 (b). This allows significantly improved power output for a given track current and volume of PU ferrite.

The results of a simulation where the width of the PU was varied from 10mm to 300mm under the same conditions are shown in Fig. 7. The increase in P_{su} as the PU is made wider is reasonably linear however the volumetric efficiency decreases. This is partly due to the end effect and the finite width of the track. Flux from sections of wire not directly under the PU will get attracted to the ferrite and pass through the coil. As the PU is made wider and approaches the track width, the contribution diminishes. The end effect is responsible for the initial large negative gradient of the VA per unit of ferrite volume curve. The outer edges of the front and back of the PU attract a fixed amount of flux that contributes to the total P_{su}. Very narrow PUs have this additional flux component as well as the component due to the width of the PU resulting in a high power per unit volume.

A practical RPEV system needs to deliver 20kW with an air gap of 150-200mm. All subsequent simulations have been done with a 175mm air gap for a fair comparison. The track current has been increased to 250A as industrial IPT systems use currents in the range of 100-300A at ~40kHz. A series of simulations were run to determine the effect of track pitch on uncompensated power. The length of the 300mm wide PU was constantly adjusted to be 4 times the track pitch. A solid ferrite sheet was added under the track to increase power transfer. The results of the simulation along with a volumetric comparison are shown in Fig. 8. The increase in coupled power for a track with and without ferrite is relatively linear at pitches greater than 150mm. Based on these results a track pitch of 250mm and width of 1350mm has been chosen for subsequent simulations. The P_{su} at a 250mm pitch is 11kVA and with a Q between 2 to 3, the power output is 20-30kW, which should be sufficient for an RPEV.

B. Placing Ferrite under the Track

The cost efficiency of placing a solid sheet of ferrite under the track is a concern and adds significantly to the primary inductance. Simulations were done to determine the effect of placing continuous ferrite strips along the length of the track. The material used was N87 with a relative permeability of 2400. The results are shown in Fig. 9. There are two families of curves, one for P_{su} and the other for a volumetric comparison based on the track ferrite volume. The intersection with the y-axis is for a track without ferrite, each curve with markers is for tracks with 5 or 10 ferrite strips and the list of numbers maps to the data points.

The practicality of constructing a track with embedded strips may be difficult, therefore a simulation was done where the relative permeability of a solid slab under the track was varied from unity to 3000. The conditions are the same as for the previous simulation. The results are shown in Fig. 10, as expected, the P_{su} is 11 kVA when the permeability is 2400. This curve can be used to match track ferrite designs with the results in Fig. 9. For example, the same performance is achieved with 10 evenly spaced 20mm wide strips or with a solid sheet of material with a relative permeability of 400. As such, it may be also possible to use ferrite powder to simplify track construction.

C. Final Simulated System Performance

A practical RPEV system that operates with an air gap of 175mm has been designed based on previous simulation results. The total track width is 1550mm, corresponding to a midsection width of 800mm and a pitch of 250mm. Eight 20mm wide ferrite strips with a relative permeability of 2000 have been placed equidistantly under the straight section of the tack. A power profile is shown in Fig. 11. Each line represents the P_{su} along one period of a phase at various

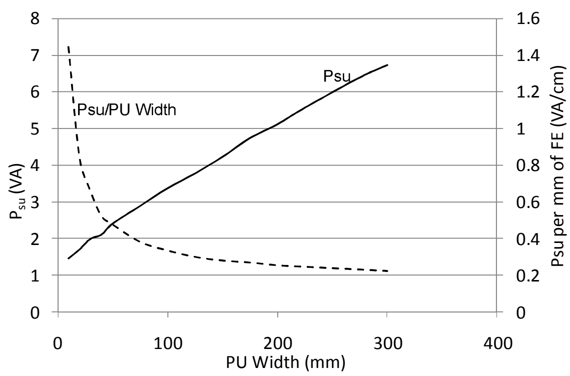

Fig. 7. Effect of PU width on P_{su} at an air gap of 60mm (65mm pitch)

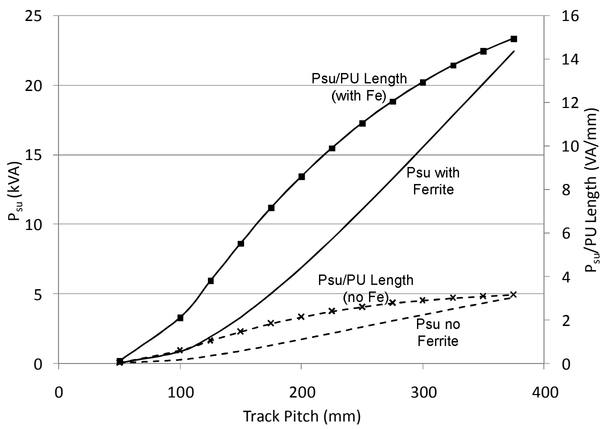

Fig. 8. Increasing track pitch with a matched PU

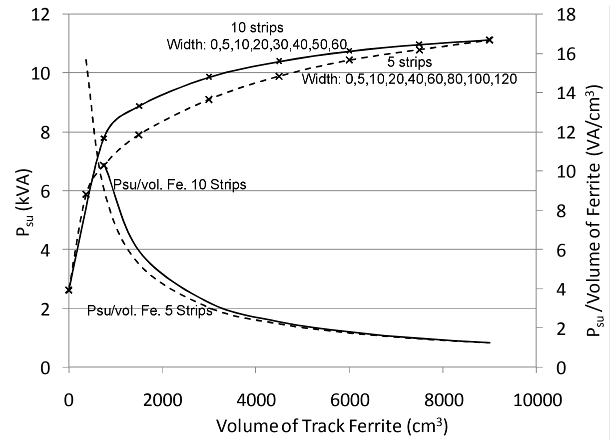

Fig. 9. Varying the volume of track ferrite by using 5 or 10 strips of varying widths, the track is 600mm wide.

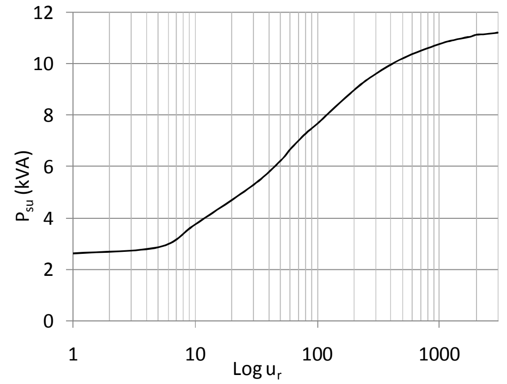

Fig. 10. Varying the relative permeability of a solid sheet under the track.

offsets from the centre. Assuming a Q of 5 is possible, the power to the EV will be a constant 30kW over an 800mm wide zone. The ripple in the power profile when the PU is close to the edge of the track is due to the curved end sections, as there is slightly more coupling when the PU is above two overlapping curves than when it is over one.

V. Conclusions

Inductive Power Transfer is a suitable means for powering EVs through the road, however full scale implementation has been infeasible due to poor horizontal tolerance offered by existing IPT track topologies. In this paper a new three phase unipolar track has been presented. This track has balanced mutual inductance between phases making it easier to drive than the bipolar design. Another advantage is that increasing horizontal tolerance only adds linearly to copper loss and cost.

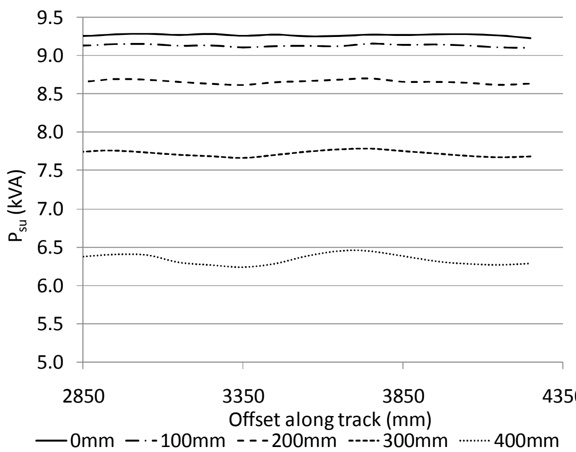

Fig. 11. Performance of a practical RPEV system at 175mm separation.

A small scale prototype has been constructed to verify the balanced interphase coupling and to compare measurement with simulation. Results of the physical prototype differed from the finite element simulation model by 5% at most allowing a practical design to be simulated with confidence. Variables considered were the PU length and width, track pitch and width, as well as ferrite structures under the track. Volumetric comparisons were used to ensure the PU produced the most power for the lowest volume of ferrite. The simulated practical track is able to deliver 30kW with an air gap of 175mm over an 800mm wide zone.

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