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Inductive Power Transfer Pickups
for High Demand Applications

By

Stefan Raabe

A thesis submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy in Electrical and Computer Engineering,
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This thesis is for examination purposes only and may not be consulted or referred to by any persons other than the examiner.
For Dad
Abstract

This thesis presents two new high power pickups for two distinctly different distributed Inductive Power Transfer (IPT) systems. IPT is a technology that enables the transfer of power without contact, either point to point for charging applications, or in a distributed system to power mobile loads along a track or monorail. The thesis is concerned with aspects of the operation of these two systems.

The first pickup, termed the quadrature pickup, is designed for greater lateral tolerance across the track while receiving power, and is primarily for Automatic Guided Vehicles and roadway systems, where the pickup is above the track and it is desirable not to constrain the AGV operation to the centre of the track. In comparison, the second pickup, termed the coaxial pickup, is a highly constrained pickup for a monorail track, designed for very high power transfer. This pickup uses a single turn copper pipe winding surrounded by toroidal ferrites to achieve a high coupling factor while limiting voltages to below acceptable safety standards.

The magnetic performance of the quadrature pickup is analysed first. This pickup achieves greater tolerance across the track by coupling both the horizontal and vertical components of the magnetic flux generated above the track by an elongated winding. Two different designs are compared using both computer simulation and practical measurements. These pickups are based on ferrite structures used in modern commercial AGV pickup designs but are significantly improved here. The chosen design uses two coils in geometric quadrature, and was developed further with simulations to balance their contributions based on the pickup receiver location over the track.

As shown, the contribution of these coils cannot be balanced simply by changing the magnetic design. In consequence, partial series tuning is used together with parallel tuning to achieve this balance. The effect this compensation has on both the reflected impedance of the pickup and magnetic flux within the pickup ferrite was investigated. It is shown that provided this partial series tuning is constrained to an operating current boost \((Q_f)\) of less than 2, partial series compensation is desirable. The efficiency of the pickup was also considered particularly with areas where losses are introduced. Extra loss is incurred with the addition of the second coil to the pickup. A modified controller is presented which disables each coil if it is not contributing significantly to the output.
An alternative to improve pickup tolerance is to modify the track. The quadrature pickup is shown to be compatible with all track configurations whether single or poly-phase. Both meander and poly-phase tracks were investigated, and a new configuration, termed the double conductor repeated single phase track was introduced. For the meander track, the quadrature pickup eliminates null power points exhibited by other pickups. On both three and two phase tracks, the quadrature pickup receives greater power, and allows the track conductors to be spread more widely, offering greater lateral range. However, the double conductor repeated single phase track offers a similar power output to the three phase track and improves on a two phase track. This single phase track topology is preferable considering the difficulty in tuning and compensating poly-phase tracks, and has particular advantages in terms of load sharing if multiple inverters in parallel are used to drive the track.

A preliminary design of the coaxial pickup was investigated through simulation, and two prototypes at different scales have been constructed. Two different control circuits are presented to boost the low voltage of the pickup to commercial standards of 330V or 560V. Both these circuits are divided to switch discrete amounts of power to reduce the impact on the power supply. Additionally, interleaved switching is used to distribute the losses and heating through the pickup.

The thesis concludes with a summary of the advantages of the quadrature pickup. On a single phase track with no modification to the ferrite structure, the quadrature pickup can deliver 400W over a range of ±110mm – 10 times the range of a comparable pickup that captures only the vertical flux with a range of ±10mm. When operated on the new double conductor repeated single phase track, the pickup can deliver 5 times the power (2kW) over the same range. A final proposed change to be implemented on a commercial prototype is a split winding horizontal coil which further increases the contribution of the horizontal coil.

The work described in this thesis represents improvements far beyond what was considered possible at the start of the work and makes a significant contribution to having IPT price competitive with conductor bar technology while having all its attending advantages.
There are many people I would like to thank for their support and encouragement during this research. Each of these people have helped me to reach this achievement.

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Nomenclature

Definitions

Bipolar  Describes a track in which the pick-up interacts with both the forward and return current path of any phase.

Unipolar  A track in which the pick-up only interacts with the magnetic field from the forward current path of any phase.

Acronyms

AGV  Automated Guided Vehicle

AWG  American Wire Guage

CAD  Computer Aided Drafting

DEP  Dominant Electrical Parameter

EV  Electric Vehicle

FEM  Finite Element Modelling

ICCF  Inter Conductor Cancellation Factor

IPT  Inductive Power Transfer

PWM  Pulse Width Modulation

ZCS  Zero-Current Switching

ZVS  Zero-Voltage Switching

Symbols

\( C_1 \)  Track (primary) tuning capacitor

\( C_2 \)  Pickup (secondary) tuning capacitor

\( C_{2H}, C_{2V} \)  Horizontal and vertical pickup coil tuning capacitor

\( C_{L2} \)  Partial series tuning capacitor

\( C_{L2H}, C_{L2V} \)  Partial series tuning capacitor for the horizontal and vertical coils

\( \delta_{\text{Slot}} \)  Difference between the copper slot and ferrite slot (mm)
<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_x$</td>
<td>Horizontal displacement of the pickup ferrite relative to the track centre.</td>
</tr>
<tr>
<td>$d_y$</td>
<td>Vertical displacement of the pickup ferrite relative to the centre of the track conductors.</td>
</tr>
<tr>
<td>$I_1$</td>
<td>Primary (track) current</td>
</tr>
<tr>
<td>$I_2$</td>
<td>Current in the pickup coil</td>
</tr>
<tr>
<td>$I_{SC}$</td>
<td>Short circuit current of the pickup coil</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Pickup coupling efficiency metric</td>
</tr>
<tr>
<td>$L_1$</td>
<td>Inductance of the track</td>
</tr>
<tr>
<td>$\Delta L_1$</td>
<td>Change in track inductance</td>
</tr>
<tr>
<td>$L_2$</td>
<td>Inductance of the pickup</td>
</tr>
<tr>
<td>$L_{2H}$, $L_{2V}$</td>
<td>Inductance of the horizontal and vertical pickup coils</td>
</tr>
<tr>
<td>$L_{2H-A}$, $L_{2H-B}$, $L_{2V-A}$, $L_{2V-B}$</td>
<td>Inductance of the horizontal and vertical split coil halves</td>
</tr>
<tr>
<td>$M$</td>
<td>Mutual inductance</td>
</tr>
<tr>
<td>$N_1$</td>
<td>Number of turns in the track inductor</td>
</tr>
<tr>
<td>$N_2$</td>
<td>Number of turns in the pickup coil</td>
</tr>
<tr>
<td>$N_{2H}$, $N_{2V}$</td>
<td>Number of turns in the horizontal and vertical coil</td>
</tr>
<tr>
<td>$N_{2H-A}$, $N_{2H-B}$, $N_{2V-A}$, $N_{2V-B}$</td>
<td>Number of turns in the horizontal and vertical split coil halves</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency</td>
</tr>
<tr>
<td>$\Phi_2$</td>
<td>Flux in the pickup coil</td>
</tr>
<tr>
<td>$P_{DC}$</td>
<td>DC output power</td>
</tr>
<tr>
<td>$P_{Diode}$</td>
<td>Power loss in the diodes</td>
</tr>
<tr>
<td>$P_{H}$, $P_{V}$, $P_{Both}$, $P_{Total}$</td>
<td>Real power delivered by each inverter to the horizontal, vertical, both coils and the total pickup</td>
</tr>
<tr>
<td>$Q$</td>
<td>Quality factor</td>
</tr>
<tr>
<td>$Q_I$</td>
<td>Operating current quality factor</td>
</tr>
<tr>
<td>$Q_L$</td>
<td>Natural quality factor of an inductor</td>
</tr>
</tbody>
</table>
Q_v Operating voltage quality factor
R_L Load resistance
S_U Uncompensated power of the pickup coil (Defined as $V_{OC} \cdot I_{SC}$)
S_H, S_V, S_Both, S_Total Power delivered by each inverter to the horizontal, vertical, both coils and the total pickup
µ_0 Permeability of free space
µ_r Relative permeability of the pickup ferrite
VAR Reactive power
VAR_H, VAR_V, VAR_Both, VAR_Total Reactive power delivered by each inverter to the horizontal, vertical, both coils and the total pickup
V_F Diode forward voltage drop.
V_2 Voltage across the pickup coil
V_{OC} Open circuit voltage of the pick-up coil
V_r Reflected voltage from the pickup to the track
V_{Res} Resonant voltage across the pickup resonant tank
ω Operating frequency across the power supply
ω_0 Resonant frequency of the pick-up or track network.
X_Both, X_Ferrite, X_Total Reflected reactive load on the track due to both coils, the ferrite and the total pickup.
X_r Reflected reactance from the pickup to the track
Z_r Reflected impedance from the pickup to the track
1 Introduction

1.1 Introduction

Inductive Power Transfer (IPT) is a method of transferring power wirelessly between two electrically isolated systems, allowing these two systems to be separated by a reasonable air gap while supplying energy to vehicles and devices for a variety of applications. IPT was conceptualised in the late 1800’s by notable people such as Nikola Tesla, as it is based on fundamental principles of electromagnetism. Within the past few decades, advances in power electronic devices and materials have allowed practical IPT systems to be achieved.

This chapter presents a brief history of the development of IPT. A number of commercial implementations of IPT systems are introduced, outlining the current state of these systems and the improvements still to be developed. This thesis focuses on two particular demands; increasing the lateral range of movement over which power can be delivered for Automatic Guided Vehicle (AGV) systems, and to further increase the power rating of monorail based IPT systems.

1.2 Electromagnetism

The principles of inductive power transfer have been understood for nearly two centuries; the basis of them is described by the fundamental laws of magnetism. In 1820, Hans Christian Ørsted discovered that electricity and magnetism were linked, when he observed a current carrying wire would deflect the needle of a nearby compass. Ørsted was unable to explain this phenomenon, but a year later the French physicist André-Marie Ampère formalised the interaction into what has become a fundamental building block of electromagnetism [1], known as Ampère’s law:

\[ \oint_C H \cdot dl = I \]  

(1.1)

This equation states that the line integral of the magnetic field intensity around a closed loop is equal to the current flowing through it.

In 1831, Michael Faraday discovered that a magnet moving through a coil of wire caused a current to flow in the wire. He demonstrated that a changing magnetic field induced a
changing electric field, known as magnetic induction. This is formalised in Faraday’s law, given by:

\[ V = -N \frac{d\Phi}{dt} \]  

(1.2)

Based on the previous work of Ampère and Faraday, Scottish physicist James Clerk Maxwell presented a set of 20 equations to the Cambridge Philosophical Society in 1856, unifying all electric and magnetic theory into an encompassing electromagnetic field theory. These were later published in his paper "On physical lines of force" in 1861. In 1864 he included light in his unifying theory in the paper "A dynamical theory of the electromagnetic field". His equations first appeared in their modern form of four differential equations in 1873 in Maxwell’s textbook, “A Treatise on Electricity and Magnetism”.

### 1.3 History of IPT

Many attempts have been made to transmit power wirelessly, most notably those of Nikola Tesla in the late 1800’s and early 1900’s. In 1894 Tesla successfully demonstrated wireless illumination of incandescent lamps by means of resonant inductive coupling. Interestingly, in later years Tesla’s research changed direction to attempting to use the resonant frequency of the earth to transfer power around the globe. He writes "the inferiority of the induction method would appear immense as compared with the disturbed charge of ground and air method."

In the same year, Maurice Hutin and Maurice LeBlanc were awarded U.S. Patent #527,857 describing a loosely coupled inductive power transfer system operating at 3kHz [2]. The objective was to replace the third rail and overhead lines of a train with this system. Both the primary and secondary coils were compensated to overcome the poor magnetic coupling. However, the switch devices and capacitors available at the time prevented them from transferring significant amounts of power.

In 1971, Prof. Don Otto of the University of Auckland, New Zealand developed a small trolley powered by induction. Later in 1974 he was awarded a patent proposing the use of IPT to power moving vehicles at an operating frequency of 4-10kHz [3]. This was now possible due to the advent of power semiconductors and the development of capacitors, wire and ferromagnetic material. As a result, the ability to make efficient low cost converters to supply a high frequency track current became less of a barrier. The problem was to control and regulate the power on the secondary side, especially if multiple vehicles were to be powered by a single supply.
In 1979, a feasibility study was undertaken for a roadway powered electric bus for Santa Barbara, based on the research of Bolger [4, 5]. A 35 seat bus was fitted with a mechanically lowered pickup, capable of 64kW over a gap of 58 – 80mm when powered by a track with 200A at 100 – 400Hz. The output was regulated using a switched AC capacitor bank, with an efficiency of 65%.

In 1994 Boys and Green proposed a modified boost topology which decoupled the secondary coil (or pickup) from the primary, allowing multiple pickups to operate at significant amounts of power [6, 7]. This design made it possible to apply IPT to industrial applications, a selection of which are presented later in the chapter.

### 1.4 Benefits of IPT

Inductive Power Transfer systems offer a number of advantages compared to traditional brush/contact or festoon systems, due to the contactless nature of IPT. These advantages include:

- **Clean** – There are no wearing contacts or brushes to produce debris.
- **Electrically Isolated** – Similar to a transformer, no electrical connection exists between the power supply and the pickup, only a magnetic link.
- **Electrically safe** – In addition to being isolated, no contacts are exposed.
- **Can be used in dirty or wet environments** – Because of the contactless nature, the enclosure can be sealed from the environment easily.
- **Intrinsically Safe** – The enclosure can easily be made airtight for use in gaseous environments.
- **Flexible, rapid movement.** – No spools or festoons to limit the speed of the device to be powered, and more speed and flexibility than brushed contact systems.

For the reasons outlined above, Inductive Power Transfer is an excellent choice for many applications, although early systems were naturally expensive and the applications were limited to those where the benefits outweighed the cost. As IPT is further developed, new applications will emerge and the costs of these systems will be reduced.

### 1.5 IPT systems in Industry

#### 1.5.1 Monorail Systems

One of the earliest commercial implementations of IPT technology developed by the University of Auckland was undertaken in conjunction with Daifuku, a company making clean
room, car manufacturing and stacking systems. A 400W IPT pickup, shown in Figure 1-1, was developed for Daifuku’s Ramrun system starting in 1989, and was successfully developed into the first monorail system using IPT in 1993 [8]. This line of products is used in vehicle manufacturing plants to transport car bodies, shown in Figure 1-2, with the IPT version (termed HID by Daifuku) providing clean and quiet operation. Daifuku’s automotive products were first installed at Toyota’s Motomachi factory in 1959, and these have been developed to include HID systems that are now used extensively throughout Japan and the world [8].
The contactless nature of IPT means that no debris (particularly carbon dust) is produced from abrasion of contacts and brushes. Because of this, Daifuku use IPT systems in their Automated Cleanroom line of products. These systems manufacture computer CPU’s and other Integrated Circuits (IC’s), and also flat panel displays such as Plasma and LCD screens, where the smallest foreign particle can contaminate these products making them unusable. Daifuku’s products are used for transporting and storing the semiconductor material (Figure 1-3). A notable achievement is their ability to handle fragile (0.7mm) glass substrates while their 10th generation systems can handle panels of 3.5m x 3.5m [9]. As flat panel screen sizes continue to increase, further development of the technology will be required. The IPT system powering these products is required to deliver more power without a significant increase in pickup size. This challenge is a motivating factor for part of this thesis.
Other companies have also released monorail based IPT products. The two most important ones are Wampfler and Vahle, both of Germany. Unlike Daifuku, who sell manufacturing lines, these companies sell IPT systems (Figure 1-4), allowing them to be installed in a number of applications. Wampfler’s IPT® Rail systems have been installed at theme parks such as the Hermes Tower in Hannover, Germany (2000), and the Splash Battle rides in the Netherlands and California (2005/2006); as well as car manufacturing plants such as Mitsubishi in Australia and Kia in Slovakia (2004/2005).
1.5.2 Automatic Guided Vehicles

Other products offered by Wampfler and Vahle are their Flat IPT pickups, shown in Figure 1-5, often used in Automatic Guided Vehicles (AGV’s). These pickups do not protrude into the track loop as in Monorail systems, but sit above the track, making them ideal for floor based systems. These systems are extensively used in car manufacturing, commonly in engine and gearbox assembly lines, such as those used at Audi and BMW shown in Figure 1-6. These systems have been installed worldwide, at manufacturing plants such as DAF in the Netherlands (2002), GM in China (2006), and Mercedes in Germany (2007) [10-12].

As the pickup is not physically constrained to the track, these AGV’s can freely move on and off the track. However, currently they only receive power within a small range across the track of approximately ±10mm, thus on board storage must be used if large movements are necessary. Typically, an electronic guidance system is used to keep the pickup located...
above the track. It is desirable to allow power delivery over a greater range of movement, without the need for on board storage. The primary focus of this thesis investigates a pickup design to achieve this.

Figure 1-6: Wampfler IPT systems installed on AGV's in car manufacturing plants for (a) BMW, (b) Audi.

1.5.3 Battery Charging Systems

A common application for IPT systems, particularly lumped systems is battery charging. These can range from low power devices such as biomedical implants and consumer electronics such as mobile phones and laptop computers, to high power systems for charging electric vehicles.
1.5.3.1 Electric Vehicles

In the early 1990’s, the Clean Air Act of California was passed by the Californian Air Resources Board (CARB) to increase the sales percentage of zero-emission vehicles from each car maker to 2% by 1998, and 10% by 2030 [13]. The most noteworthy vehicle designed to meet this obligation was the EV1 produced by General Motors, which featured an inductive charging paddle for safety reasons, shown in Figure 1-7. This charging system was also used on the Toyota RAV4 and Nissan Altra electric vehicles, and outlined in the Society of Automotive Engineers standard J-1773 in 1995 [14]. This charging system fell out of use as these electric vehicles went out of production, and the safety of conductive connectors (which at the time were more cost effective) was addressed.

![Image of inductive charge paddle system](image)

**Figure 1-7: Inductive Charge Paddle system outlined in the SAE J-1773 Standard.**

In 1996, the University of Auckland in conjunction with Wampfler AG developed an inductive charging system for an electric bus used at the Whakarewarewa Geothermal park in New Zealand. This system was mounted underneath the vehicle and within the road, allowing for opportunistic charging while passengers embarked and disembarked [15]. A distributed IPT system was used (albeit with a very short track), where no ferrite was present in the track. Flat pickups based on the research in [16] received the power to charge the vehicles batteries.
From the work at Whakarewarewa, Wampfler started the IPT® Charge line of products (Figure 1-9). A new lumped IPT system using a buried track coil (Figure 1-10c) and a pad pickup (Figure 1-10b) were developed that allows charging at 60kW for 10 minute intervals, but required that the coils be mechanically lowered close to the road surface (Figure 1-10d). This system was first installed in Genoa, Italy in 2002 to service the San Marino Hospital. 8 buses were installed with this system, with a single charging location [17]. The system was also installed in Turin, Italy in 2003, covering two bus lines each 10-12km long [18]. A total of 23 buses were outfitted with IPT® Charge products, with two charging points per bus line. However, beyond these two installations, where electric buses were used to protect the sensitive architecture of the towns, pure electric buses have not been cost effective, and hence IPT charging solutions saw limited use. This is now beginning to change with the new battery technologies available.
Figure 1-9: Conceptual IPT® Charge system, with the primary power supply and track in yellow, and pickup and regulator in blue.

Figure 1-10: Wampfler IPT® Charge System on electric buses in Genoa, Italy. (a) Electric Bus, (b) IPT Pickup, (c) buried IPT Track, (d) pickup lowered into position for charging.
With the growing popularity of plug-in hybrid and electric vehicles, IPT charging solutions have seen a renewed interest. In 2010, UniServices, the commercial arm of the University of Auckland, helped establish a new company called HaloIPT [19]. This company is currently developing stationary IPT charging systems for electric vehicles suitable for installation in garages and public parking spaces, shown in Figure 1-11. These systems are capable of transferring 3 – 7kW over a gap of 400mm, at efficiencies greater than 85% and a power factor of 0.95. A further goal is to produce a charging lane to recharge moving vehicles. Additionally, Conductix-Wampfler has reintroduced their IPT® Charge systems [20], and Korea Advanced Institute of Science and Technology (KAIST) are developing their own vehicle charging system. Discussions are underway to produce a standard for IPT based vehicle charging systems.

![Stylised IPT Charging system from HaloIPT, showing transmitting and receiving pads on an electric vehicle.](image)

1.5.3.2 Consumer Device Charging

IPT charging applications are not limited to high power systems such as charging electric vehicles. A lot of research has gone into miniaturising and simplifying IPT systems to provide a cost effective charging solution for consumer devices such as mobile phones and laptops. Typically these consist of a charging mat on which these devices are placed, allowing opportunistic charging, and reducing the cable clutter of chargers for a growing number of portable devices. In 2010, the Qi standard for charging small consumer devices was released by the Wireless Power Consortium, a cooperation of independent companies [21]. One of the first products released to this specification is the Energizer Inductive Charger [22], shown in Figure 1-13. Currently, receiver sleeves exist for the Apple iPhone and RIM
Blackberry, and recently HTC and LG have announced the incorporation of Qi receivers in their latest phones to be released in 2011.

![Palm Touchstone and Powermat products for charging portable consumer devices.](image1)

**Figure 1-12:** (a) Palm Touchstone and (b) Powermat products for charging portable consumer devices.

![Energizer Inductive Charger certified to meet the Qi wireless charging standard](image2)

**Figure 1-13:** The Energizer Inductive Charger certified to meet the Qi wireless charging standard

### 1.5.4 Other Applications

Another successful application of IPT is to provide power for LED road markers. These systems are produced by 3i innovations (originally Hardings Smartstud) and the first installation of their system was in the Terrace Tunnel in Wellington, New Zealand in 1996 [23]. These systems are used worldwide, particularly in tunnels to enhance visibility and increase safety, as shown in Figure 1-14. The advantage of using IPT is that the cable can easily be buried in the road, and the road markers glued to the road surface. If a road marker fails, the others continue to operate. A further advantage of this system is that communications can be incorporated into the system, allowing smart traffic management by turning off or adjusting road marker colours.
Figure 1-14: IPT Powered LED road markers (a) on a double left turn, (b) in the Terrace Tunnel in Wellington, New Zealand.

The applications described in this chapter represent only a sample of applications for IPT systems. As the technology is developed further and costs reduced, the use of IPT will become more widespread.

1.6 Motivation for the Thesis

With the growing use of IPT systems within industry, there is a demand to increase the rated power and extend the capabilities of existing systems. Predominantly, distributed IPT systems are used to replace festoon and electrified rail systems because of the safety and cleanliness of these contactless systems. These are implemented as floor based systems for AGV’s, where the trolley and IPT pickup are physically unconstrained, and for monorail based systems where the pickup is constrained to move along the rail.

The goal of this thesis is to improve high power IPT pickups used in distributed IPT systems for two notable applications; increasing the power delivery range of AGV pickups, and increasing the power delivery of highly constrained monorail pickups without a significant increase in size. A significant focus is on the magnetic design of these pickups, made possible with the advancements in computer simulation software and techniques.

1.7 Contributions of the Thesis

This thesis investigates two new pickup designs for distributed IPT systems. These designs fall at the opposite ends of the application range and movement; with one being largely unconstrained in all directions, and the other highly constrained except in one direction. The first design, which is the primary focus of this thesis, aims to improve the lateral tolerance of
pickups for Automatic Guided Vehicles (AGV's). This is to operate on both existing tracks, and new track designs which also extend this lateral range.

The second design aims to improve the magnetic coupling of the pickup to the track to achieve high power delivery, while overcoming limitations of traditional pickup designs at these power levels.

1.7.1 Magnetic Design of a Quadrature Pickup

Traditional pickups typically contain a single winding, which predominantly captures magnetic flux in a single direction. The quadrature pickup contains two coils which capture both horizontal and vertical components of flux. The combined output does not suffer the nulls present in the output power profile of traditional pickups, and as such, the lateral tolerance of the pickup is improved. Chapter three investigates the magnetic design of this pickup primarily through simulation. Based on a commercial pickup structure, the ferrite in the pickup is modified to balance the contribution of the two coils while minimising impacts due to the addition of a coil.

1.7.2 Tuning and Control of a Quadrature Pickup

One of the key considerations in designing the quadrature pickup is balancing the contributions of the two windings. The output from each coil cannot always be balanced by the magnetic design alone, and further tuning compensation is required. Chapter four investigates partially series compensating the lower output coil to match the output of the two coils, and compares this to a quadrature pickup without this compensation which resonates up to a similar output. The effects of this tuning on the pickup magnetics and reflected impedance on the track are considered, along with the overall efficiency of the pickup. Techniques to improve this efficiency are also presented.

1.7.3 Further Lateral Tolerance of the Quadrature Pickup using Multi-Conductor Tracks

Track solutions have traditionally been used to increase the lateral tolerance range of AGV pickups, however many of these suffer from areas of low power delivery. As the quadrature pickup captures both horizontal and vertical components of the magnetic field, the use of this pickup on these tracks can further improve the power transferred and the lateral tolerance over which it is delivered. This is investigated in chapter five, where the quadrature pickup is simulated over both repeated single phase and poly-phase tracks. A superposition technique
is presented which allows these tracks to be rapidly modelled from simulations using only a single track conductor, provided no ferrite is present in the track.

1.7.4 Comparison of Multi-Conductor Tracks and Impacts on the IPT System

Conveniently, when designing IPT systems, the primary side and secondary side pickups can often be considered in isolation. However, for the final design and comparison between different designs, the entire system must be considered. Chapter six compares the multi-conductor systems presented in chapter five, considering not only the pickup output, but the track width and compensation required, and the loading on the inverters supplying pickups at various lateral offsets above the track. To determine this, a methodology to calculate the loading effects is presented [24], and the two most common pickup tuning topologies – parallel and series tuning – are investigated. This comparison is made for two cases; a 4 wire and a 6 wire track system.

1.7.5 A Highly Coupled Coaxial Pickup for High Power Applications

As IPT gains popularity, particularly for industrial applications, greater power transfer is desired. This is normally achieved using high track currents while maintaining good magnetic coupling. However, as the power of an IPT system increases, the output voltage can easily exceed levels considered safe by commercial standards, since a high number of turns are required on the pickup coil to maintain good coupling. Chapter seven introduces a coaxial pickup design for monorail applications which exhibits very high coupling for a distributed IPT system, using a single turn coil. The voltage produced is well within commercial limits, but results in much larger currents. The goal for this pickup is to eventually reach 100kW output at a standard commercial voltage.
2 IPT Fundamentals

2.1 Introduction

The purpose of this thesis is to develop two high power pickups for distributed IPT systems which focus on unique design criteria. The first is a loosely constrained pickup for use on Automatic Guided Vehicle systems, with the goal of extending the tolerance to movement across the track. The second is a very constrained pickup for high power applications.

This chapter contains a review of the basic components of IPT systems, with an emphasis on the pickup magnetic design and the work undertaken over the past two decades to make such systems possible in industry. In particular this thesis focuses on power transfer to moving secondaries along a track, rather than lumped systems for charging, therefore the review will largely focus on such systems. IPT systems can be broken into several largely independent blocks; the power supply and magnetic design of the primary side, and the magnetic design and power regulation on the secondary side. Firstly, the magnetic design of the pickup and track are examined. Techniques for tuning and regulating the output of the pickup, specifically how they affect the operation and efficiency of the IPT system are then examined. Finally, common types of power supply are examined, in order to determine the impact the various pickups and track layouts cause may be determined.

2.2 IPT System Overview

An IPT system in essence consists of two halves; a primary side delivering power, and a (or multiple) secondary side receiving power. Each half can further be broken down into electrical and magnetic functional blocks which can be examined independently.

Figure 2-1: Simplified IPT system diagram
Both the input and the output of an IPT system will be dependent on the application and environment where the system is used. The input energy source may be 12 – 48V DC for automotive and low power industrial systems, up to mains single phase and three phase inputs for high power systems. Likewise, the output can vary from low voltage outputs to levels equivalent to mains voltages.

2.3 Magnetic Structures

IPT systems transfer power across an air gap using magnetic material to provide a low reluctance path and therefore increase coupling between the primary and secondary, in much the same way as a transformer works. The magnetic structures used in these systems are a critical aspect, which have impacts on possible applications of the IPT system and the effectiveness to transfer power. These systems can be classified into two categories based on the primary track; lumped and distributed systems.

2.3.1 Lumped Systems

Lumped IPT systems usually consist of primary and secondary coils which are similar in size, and are used in applications where the movement of the pickup is limited. Typically, these systems accommodate a single pickup at a time, and are useful in battery charging systems and rotational joints. The most basic example of a lumped system is two planar coils which are axially aligned [25, 26], as shown in Figure 2-2.

![A basic lumped IPT system](image)

Air cored systems can deliver only limited power, but do have the advantage of a low physical profile. As such, these are typically used in low power applications such as Transcutaneous Implants [27-33], Sensors [34], and recently, charging of low power consumer devices like mobile phones [35-40].

Typically for high power applications, ferrite is used to further increase the coupling. Some common ferrite shapes are presented in Figure 2-3, where the application determines the
best one to use. Pot cores, shown in Figure 2-3(a) are ideally suited to transfer power across rotational joints or in rotating machines [41-53], due to the rotational symmetry of the design.

Lumped systems are also used as a plug replacement for safety in high power systems which are used by consumers, such as a plug for charging electric vehicles. With IPT, no contacts which can present a shock hazard are exposed. These systems commonly use pot cores [13, 54-59], toroidal coaxial transformers [60-62], and joined E-cores with a removable centre limb, as used in the charging system for the GM EV1 electric vehicle, shown in Figure 2-3(d). Such systems must adhere to the standards published by the Society of Automotive Engineers, SAE J-1773, which provides guidelines when implementing a closely coupled inductive charging interface for electric vehicles.

![Figure 2-3: Common lumped IPT systems using ferrite cores: (a) pot core, (b) U Core, (c) co-axial, (d) joined E-Cores with removable centre limb](image)

While such plug replacement systems offer safety advantages over standard electrical plugs, the key feature of IPT, its contactless nature, is not used to the full advantage. Ideally, the air gap of a lumped IPT system is sufficient so the primary may be fixed to the road surface, and the secondary to the underside of the vehicle. Designs such as the Flat-E cores shown in Figure 2-4 can be used to achieve this. These designs provide the convenience of not having to plug in cables, and opportunistic charging at traffic lights and bus stops is possible. Some of these systems have already been implemented [15, 63-66], and is seeing a resurgence with the advent of new electric and plug in hybrid vehicles. The considered applications in
this thesis are based for continuous power to moving systems relative to that track. The design for such distributed systems are quite difficult and are discussed following.

Figure 2-4: Flat-E cores with greater separation

2.3.2 Distributed Systems

In contrast with lumped IPT systems, distributed systems are designed to allow free movement of the pickup, predominantly in one direction of motion. To achieve this, the track is typically an elongated loop of cable, over which multiple pickups may operate. Ferrite is not usually included in the track, as the cost of including this over large distances is prohibitive.

Distributed tracks can be divided into two categories, unipolar and bipolar tracks. This classification is particularly useful when describing multi-phase tracks (presented in the following section). As an example if a three phase track is created using a unipolar structure then the track conductors are star connected at the opposite end to the power supply, while a bipolar structure has each conductor return wire brought back to the power supply, forming individual loops for each phase [24, 67-69]. The tuning and power supply design will differ for each of these options. If the number, geometry and phase difference of the track conductors are constant then the output of a pickup powered by such tracks will be indentical, i.e. a six phase unipolar track is equivalent to a three phase bipolar track.

While theoretically the same classification exists for single phase tracks, practically the track must have a path for the track current to return. As such, single phase unipolar systems are implemented using a loop where the return conductor is sufficiently distant so as not to couple with the pickup [4]. An example of this and a single phase bipolar track are shown in Figure 2-5(a) and (b) respectively.
The single phase unipolar track has two notable disadvantages. The inductance of the track is very large due to the area inside the track loop, and the magnetic field generated by the track is not well contained. Regulations exist which limit levels of public exposure to magnetic fields, the predominant European standard being EN 50366, restricting the magnetic flux density to 6.25µT for frequencies between 800Hz – 150kHz. The small loop area of the bipolar track reduces both these issues, and for this reason is the preferred topology for such distributed tracks.

2.3.2.1 Monorail Pickups

Distributed systems can further be categorised into systems where the pickup protrudes into the track loop – used in monorail systems shown in Figure 2-6, or has a clearance between the track loop and the pickup – typically used for Automatic Guided Vehicle (AGV) applications, shown in Figure 2-7. Various pickup shapes can be used on monorail systems, and are shown in order of increasing coupling in Figure 2-6. The first pickup uses a U-core ferrite, and is used on a single phase unipolar track [70, 71]. As previously explained, the unipolar track is not often used. An extension of this pickup is the E-core, which couples with both track conductors [6, 72-75]. The magnetic field from the current in these cables is orientated in the same direction within the pickup coil, giving approximately twice the coupling of the U-core. Variations on this shape is the H-core and S-core pickups [72], and the coaxial pickup [76-81].

Of these pickups, the E-pickup is typical of commercial monorail IPT systems. The shape of the pickup lends itself to easy removal from the track when necessary, while maintaining good coupling. One key aspect of all monorail pickups is the physical limitations to the movement of the pickup. Because they protrude into the track, the pickups can only move in the direction of the track conductors with any degree of freedom.
2.3.2.2 Coaxial Pickup

The coaxial pickup [76-81] has the best coupling to the track of all the monorail pickup designs presented above. This is ideal for pickups designed for very high power output. This tight coupling is achieved by using a copper pipe winding with toroidal ferrite. However, it is difficult to have multiple turns on this coil [60], and the resulting output current is very large. Past applications of this coaxial pickup simply rectify the output into a capacitor bank, with any output regulation controlled by the primary supply. Because of this, tuning of the secondary coil is avoided, which limits the coaxial pickup to designs that fully surround the track (with minimal air-gaps) in order to reduce leakage inductance of the pickup.

2.3.2.3 AGV Pickups

AGV pickups do not have the same physical constraints as monorail systems and the pickup is able to move in three axes of motion. Naturally, to achieve this, the pickup cannot protrude into the track. Common pickup shapes for AGV systems are shown in Figure 2-7. However, while pickup movement is not restricted physically, the power coupled by the pickup only remains constant for movement in the direction of the track. The power decreases rapidly as the pickup moves laterally across the track from centre or is raised further above the track, and is dependent on the pickup shape.
Due to the fact that the pickups do not protrude into the track, and the proximity between these is much greater, typical AGV pickups can be separated into two categories depending of the predominant direction of magnetic flux coupled to the pickup. The simplest is a flat pickup, shown in Figure 2-7(a), which captures horizontally orientated flux. Maximum flux is coupled when the pickup is centred over a track conductor. Furthermore, the width of the pickup can be increased to allow more lateral tolerance.

The second pickup is the Flat-E pickup, which captures vertically orientated flux as shown in Figure 2-7(b). This pickup couples maximum flux when located to the side of a conductor. This pickup is ideally suited for bipolar tracks, as the flux from each conductor combine in the centre of the track between the two conductors, resulting in a large vertical flux. However, the width of the pickup is dependent on the width of the track, so the lateral range of the pickup is not easily increased.

A new pickup topology was first suggested in [16] to capture both horizontal and vertical flux components, by combining the windings of the two pickups above although little analysis or optimisation was undertaken. By capturing both directional components of flux, the range of lateral movement over which power can be delivered is increased. This pickup is known as the quadrature pickup, and its design, means of control and impact on the system is the primary focus of this thesis.

2.3.3 Extending the Range of Distributed AGV Systems

Distributed systems predominantly extend the range of motion in a single direction – along the length of the track loop. For AGV applications, where the pickup is not physically constrained to the track, a lateral range of motion is desirable. This can be achieved by modifying the pickup or the track, or a combination of both. Pickup solutions include the use of multiple offset pickups [16], or recently the quadrature pickup described above.
It is more common for the track to be modified to increase the lateral range. In particular, for applications where multiple vehicles operate on the track, it is more cost effective to modify the track rather than all the pickups in the system.

A layout which increases the lateral range and is simple to implement is the meander track configuration, shown in Figure 2-8. The conductors of a single phase track are repeated by laying the track in a serpentine, such that the phase between neighbouring conductors is 180 degrees. However, like a standard single phase track, at various lateral offsets, the flux is predominantly horizontal or vertical in direction and standard pickups capturing one directional flux component will have null points in the output power profile.

![Figure 2-8: A meander track configuration.](image)

More recently, multi-phase tracks have been used to extend the lateral range over which power can be delivered to a pickup [24, 67, 68]. These tracks consist of multiple track conductors with currents out of phase. Typically these currents are sequentially arranged to give a flattened rotating magnetic field. A common example of this is the three phase bipolar track shown in Figure 2-9. Each of the three tracks can be driven from a separate inverter, or one inverter with three phase outputs. Each track is driven with a current which is shifted 120 degrees in phase, relative to the other tracks. Due to the bipolar arrangement, the conductors are usefully positioned to give 60 degrees phase shift in current between any neighbouring conductors. The resulting magnetic field produces a fairly constant power profile across the width of the track [24, 67, 68].
2.3.4 Finite Element Modelling

Because of the complex design of some IPT designs and the increasing emphasis on the magnetic field strength of such systems, Finite Element Modelling (FEM) software is often used to model these systems. This software allows the designer to change the track and pickup shapes easily and calculate an expected output, without the cost and time involved in physically producing the system until the design is completely developed. Popular software packages include Ansys, Comsol and JMAG, but many more are available. JMAG is used throughout this thesis. Additionally, many of these programs incorporate some form of scripting and parameter control, allowing the automation of iterative simulations, such as the movement of a pickup.

2.4 The IPT Pickup

The focus of this thesis is primarily on the design of IPT pickups, specifically the magnetic design but also covers aspects of the controller and tuning, and the impacts of these designs on the power supply.

2.4.1 Coupling Model

IPT systems transfer power in much the same fashion as transformers, albeit with a large airgap in the magnetic path. The system can be considered as a loosely coupled transformer, and modelled using the conventional transformer model with an equivalent T circuit [74, 82, 83] as shown in Figure 2-10(a), or the mutual inductance model [29, 84-86] shown in Figure 2-10(b).
The advantage of the mutual inductance model is that the power supply and pickup can be designed independently. For IPT pickups, the magnetic components are described in terms of open circuit voltage ($V_{OC}$) and short circuit current ($I_{SC}$). The $V_{OC}$ describes the voltage induced in the pickup from the primary side [6, 87, 88], and is given by:

$$V_{OC} = j\omega M I_1$$

(2.1)

where $I_1$ is the track current operating at frequency $\omega$, and $M$ is the mutual inductance between the track and the pickup.

$I_{SC}$ is given when the output of the pickup coil is connected short circuit:

$$I_{SC} = \frac{V_{OC}}{j\omega L_2}$$

(2.2)

Where $L_2$ is the inductance of the pickup coil. Combining these gives the uncompensated power, shown in (2.3), which gives a measure of how well the pickup is coupled to the track and how effective is the power transfer. It should be noted that the majority of the work at the on-set of this thesis focuses on track based systems where the pickup was constrained relative to a track without ferrite. As such only a limited appreciation of the impacts of variations in $M$ due to misalignment relative to the conductors was undertaken. In this work, this variation needs to be considered in detail.
\[ S_v = V_{oc} I_{sc} = j \omega \frac{M^2}{L_2} I_1^2 \]  

(2.3)

2.4.1.1 Magnetic Coupling Efficiency

The previous metrics for describing the performance and coupling of a pickup is dependent on the number of turns of the pickup and track, the operating frequency, and the inductance of the primary track. This is an issue in distributed IPT systems where the primary track inductance can vary depending on the power supply design, but provided the current and track geometry remains unchanged, the operation of the pickup is unaffected. A magnetic coupling metric, \( \kappa_\phi \), has recently been proposed as a means to analyse and compare pickup geometries in such distributed IPT applications [16, 89].

The standard coupling factor used when designing transformers is given by:

\[ k = \sqrt{k_1 k_2} = \frac{M}{\sqrt{L_1 L_2}} \]  

(2.4)

While quite rare, the coupling factor can be divided into \( k_1 \) and \( k_2 \), which corresponds with the fraction of \( \phi_1 \) that links the secondary coil (2.5) and the fraction of \( \phi_2 \) that links the primary coil (2.6).

\[ k_1 = \frac{\phi_{21}}{\phi_1} \]  

(2.5)

\[ k_2 = \frac{\phi_{21}}{\phi_2} \]  

(2.6)

As the primary is driven by a constant current at known frequency, the T-model of the circuit can be modified by replacing the voltage source and \( (L_1 - M) \) with a current source, removing the dependency on \( L_1 \) as shown in Figure 2-11.

Figure 2-11: Equivalent circuit with Infinite Track
Using the definition of inductance for a linear system gives:

\[
L_2 = \frac{N_2 \phi_s}{I_2} \quad (2.7)
\]

\[
M = \frac{N_1 \phi_m}{I_2} \quad (2.8)
\]

Combining these two equations (2.7) and (2.8) with equation (2.6) results in a coupling metric dependent only on the pickup geometry:

\[
\frac{M}{L_2} = \frac{N_1 \phi_m}{I_2} \cdot \frac{I_2}{N_2 \phi_2} = \frac{N_1 \phi_m}{N_2 \phi_2} = k_2 \frac{N_1}{N_2} \quad (2.9)
\]

Putting equations (2.1) and (2.9) into (2.2), and replacing the symbol \( k_2 \) with \( \kappa_\phi \) gives:

\[
I_{sc} = \frac{M}{L_2} I_1 = \kappa_\phi \frac{N_1}{N_2} I_1 \quad (2.10)
\]

The flux linkage efficiency, \( \kappa_\phi \), gives the proportion of flux that links the primary to the secondary over the total flux generated in the secondary. This is independent of the track length, and gives a measure of the effectiveness of the magnetic coupling of the pickup. An ideal pickup with no secondary leakage flux would have a \( \kappa_\phi \) of 1, but typical pickups for AGV applications range from 0.35 – 0.65. For monorail (guided) systems where the secondary ferrite structure is placed close to and around the primary, \( \kappa_\phi \) up to 0.8 can be achieved. A simple short circuit test can be used to measure \( \kappa_\phi \) using equation (2.10) above.

When designing pickups, given the \( \kappa_\phi \) for a particular magnetic pickup design, the \( I_{sc} \) can be calculated from the turns and track current. If the inductance of the pickup is also known, \( V_{oc} \) and hence \( S_c \) can also be found. For a full IPT system driving \( n \) pickups, the total coupling of the system is given by:

\[
k = \frac{N_1}{N_2} \sqrt{n \cdot \kappa_\phi \frac{L_1}{L_2}} \quad (2.11)
\]

\( \kappa_\phi \) provides an effective metric for comparing pickup coupling independent of the track inductance, and is used throughout this thesis.
2.4.2 Pickup Compensation

With the low coupling between the IPT pickup and the track, the pickup does a poor job at transferring power. This is because most of voltage is dropped across the inductance of the pickup coil. The maximum power is transferred when $R = \omega L_2$, and is given by:

$$P_{\text{Max}} = \frac{1}{2} V_{\text{oc}} I_{\text{SC}} = \frac{1}{2} M^2 \omega I_1^2$$

(2.12)

To improve the power transfer of the pickup, this coil inductance is tuned with a capacitor to resonate at the operating frequency of the track ($\omega_0$) [87]. The value of the capacitance required is:

$$\omega_0 = \frac{1}{\sqrt{C_2 L_2}}$$

$$C_2 = \frac{1}{\omega_0^2 L_2}$$

(2.13)

Different tuning topologies used to tune the pickup change both the output of the pickup and the load placed onto the track [90]. Two common topologies are the parallel tuned and series tuned pickups, shown in Figure 2-12.

Figure 2-12: (a) a series tuned pickup and (b) a parallel tuned pickup.

More recently, an LCL topology has been proposed for tuning IPT pickups [91, 92], as shown in Figure 2-13. This has a similar structure to the parallel tuned circuit, but with some of the advantages of series tuning and can be designed as a unity power factor controller for monorail systems.
The addition of the compensation capacitor boosts the voltage and current in the pickup coil. The amount of boost is called the Quality Factor, $Q_2$, and is dependent on the topology used:

$$Q_2 = \begin{cases} \frac{\omega_0 C_2 R_{EQ}}{L_2} & \text{parallel tuned} \\ \frac{\omega_0 L_2}{R_{EQ}} & \text{series tuned} \\ \frac{\omega_0 C_2 R_{EQ}}{L_2} & \text{LCL tuned} \end{cases} \quad (2.14)$$

While both the voltage and current in the resonant tank are increased by a factor of $Q_2$ (which is the loaded $Q$ of the circuit), only one of these boosted values (current or voltage) appears at the load, based on the considered topology. Parallel tuning will deliver an increased voltage to the load, as will the LCL tuning, while series tuning delivers an increased current. The resulting power is given by:

$$P_{Max} = Q_2 V_{oc} I_{SC} = Q_2 \frac{M^2}{L_2} \omega I_1^2 \quad (2.15)$$

As the pickup coil is tuned, it is sensitive to the operating frequency of the track and the resonant tank. If the pickup is not tuned accurately, the maximum $Q_2$ achieved will be limited. As such, tuned IPT pickups have a bandwidth, which is defined as the range of frequencies beyond which the maximum output power is reduced by half. For the resonant circuits considered, this is given by:

$$BW = \frac{\omega}{Q_2} \quad (2.16)$$

For most systems, operating beyond this bandwidth is impractical, due to the reduction in output power. However, the components used in the resonant tank naturally have a
tolerance, and can vary with age. This places a practical limit of approximately 10 on $Q_2$ for most IPT systems [6].

One point of difference between the tuning topologies is the reflected impedance ($Z_r$) seen by the track when operating at the tuned frequency. Just as a current in the primary track induces a voltage in the secondary coil, current in the secondary coil induces a voltage on the primary track, shown in Figure 2-10(b). This represents the load of the pickup on the power supply, where $Z_r = V_r / I_1$. The current in the pickup varies with various tuning topologies, resulting in different reflected impedances on the power supply. The $Z_r$ of the series tuned pickup is purely resistive [85, 93], and is given by:

$$Z_r = \frac{\omega^2 M^2}{R_{EQ}}$$

(2.17)

The parallel tuned pickup reflects a known reactive component as well as the resistive component from the load on the pickup:

$$Z_r = \frac{\omega^2 M^2}{R_{EQ}}(R_{EQ} - j\omega L_2)$$

(2.18)

### 2.4.3 Controller Topologies

When a pickup receiver can move relative to the primary track conductors there can be considerable variation in $M$. This combined with its operation as a resonant system means that IPT pickups do not have the natural regulation of regular transformers. As such, some form of controller is needed to regulate the output voltage across the load and ultimately avoid the pickup destroying itself by operating beyond the ratings of the components used. Ideally without regulation, the voltage across a parallel tuned pickup with no load will rise to infinity. In practice the $Q$ will be limited by the natural $Q$ of the coil which is typically $100 < Q < 400$. If $V_{OC}$ is $50 – 100$V, several 10’s kV’s can appear across the inductor and parallel capacitor. Common output voltages for industrial systems are 24V, 48V, 330V or 560V, but the output is by no means limited to these values.

Four methods of regulating the power transfer can be determined from (2.15). First, the magnetics of the pickup can be modified [94] by changing the ratio $M^2 / L_2$. To achieve this, a barrier or shield is required to change the flux that couples to the pickup. Such an arrangement is not a practical solution.
2.4.3.1 Primary Side Control

The second method of control is by modifying the characteristics of the primary side [13, 95], either by modifying the track current, or the frequency. With primary side control, the secondary circuit is as simple as possible. However, a method of communication is necessary for feedback of the output voltage to the primary side. Additionally, the track can only accommodate a single pickup, as any control will affect all pickups on the track [70, 71] and accurate regulation of each is not possible. As such, primary side control is only feasible for applications like battery charging or single vehicle systems.

2.4.3.2 Secondary Side Control

For applications where multiple pickups are required, regulation must be performed on the secondary side, so each pickup can operate independently from each other. This also eliminates the need for a communications link between the power supply and pickups, making them completely independent.

Linear regulation is possible and is the simplest form of secondary control [74]. However, due to the inherently low efficiency, these are uncommon, and switch-mode regulators are preferred.

2.4.3.3 Dynamic Detuning

A further means of regulation is dynamic detuning, where the pickup controller detuned the resonant tank of the pickup, thereby reducing the available power to the load [96-98]. The biggest disadvantage of this method is that a mistuned pickup is less efficient than one tuned correctly, and the reactive load on the track will increase as the pickup becomes mistuned. Therefore, this technique is normally used in low power applications or in charging applications where there is one supply and pickup. However, the techniques here can also be used to ensure pickups remain tuned with the track, ensuring maximum efficiency as pickup components age and values change [99, 100].

The most commonly used controller is the decoupling controller, which effectively controls the circuits loaded quality factor, \( Q \). The two common designs are the boost-mode controller for parallel and hybrid tuned pickups, and the buck-mode controller for series tuned pickups. Occasionally, buck-boost, Čuk and other regulators are also used [94].
2.4.3.4 Boost-Mode Controller

The boost-mode controller is the most common in high power IPT systems because of its simplicity and ease of control. The basic topology of this controller is shown in Figure 2-14 with a parallel tuned pickup.

![Parallel tuned pickup with decoupling "boost" controller.](image)

Figure 2-14: Parallel tuned pickup with decoupling "boost" controller.

The voltage induced in $L_2$ is tuned with $C_2$ at $\omega = \omega_0$ and used to supply current to a rectifier which converts it to dc. A large dc inductor ($L_{DC}$) is required to ensure a continuous current through the rectifier, improving the efficiency of the system [101].

The output of the circuit is typically controlled by a Schmitt trigger. The first state is when switch S is off. The current from the rectifier flows through the dc inductor and diode into the load, R and into $C_{DC}$. This causes the output voltage ($V_{DC}$) to rise. When this reaches a set upper threshold, switch S is turned on. The current from the rectifier now flows through the dc inductor and the switch, which together appear as a short circuit at dc. This collapses the resonant voltage across $L_2$ and $C_2$, effectively decoupling the pickup from the track. The voltage stored in $C_{DC}$ cannot discharge through the switch because of the blocking diode, so the current continues to flow into the load. When a set lower threshold is reached, the switch turns off and the cycle repeats.

2.4.3.5 Buck-Mode Controller

The buck-mode controller which is used for series tuned pickups works on a similar principle as the boost-mode controller; by regulating the operating $Q_2$ by decoupling the pickup [102]. As the resonant tank is in series, the switch must also be in series to block the resonant current flow and set the $Q_2$ to zero.
2.4.3.6 Circulating Current Controller

A more recent controller design is the Circulating Current Controller [98], shown in Figure 2-16. This controller allows fast switching (discussed in section 2.4.3.8) to be used without a DC inductor present. This topology employs a similar idea to a traditional controlled rectifier to regulate the output current. This requires the switches to be synchronised with the track frequency, and by adjusting the delay angle of these switches, the LCL pickup can be smoothly transitioned from full power to zero output [98]. Another advantage is that regulation can be achieved with a varying mutual coupling with the track without overloading the power supply.

2.4.3.7 AC Controller

The AC controller directly regulates the power of an IPT pickup in AC form. This is achieved using an AC switch across the load for a parallel tuned pickup (Figure 2-17a) or in series with the load for a series tuned pickup (Figure 2-17b). Regulation is achieved by adjusting the firing angle of the switches. For the parallel tuned pickup, zero voltage switching is used to clamp the voltage across the pickup to zero when the switches are on, reducing the overall output voltage [103, 104]. For the series tuned pickup, zero current switching is used to regulate the output current [105]. Both of these designs operate at high efficiencies over 90%, and have a reduced production cost.
2.4.3.8 Switching Speed

Both decoupling controllers described above can be operated under either slow or fast switching, where the switching speed refers to the frequency that the controller switch is activated at. Slow switching controllers typically operate below 100Hz, and commonly employ hysteresis feedback to ensure the output voltage oscillates between two predetermined levels to give an average output at the desired level.

Fast switching controllers operate with an essentially constant operating $Q_2$ for a given load, as the resonant voltage never fully collapses (unless no load is present). This is achieved by switching with a high frequency PWM waveform, where the duty cycle is set by the output voltage.

Fast switching has the advantage of reducing the output voltage ripple and the transient load presented to the track. However, the higher switching frequency can generate higher EMI, and high speed switching cannot be used without some form of synchronisation with tuning topologies and controllers which do not contain a dc inductor [98, 104]. Care must also be taken to ensure the frequency is high enough to avoid exciting the resonance between the AC tuning capacitor and the DC inductor [106]. In this thesis, only slow switching controllers are considered. Slow switching controllers only transfer power at rated loaded $Q_2$. They have low switching loss, but the supply must be able to cope with demands from a number of controllers switching between full and zero power. This can cause low frequency ripple on the mains if not considered in the design.

2.5 Power Supplies

IPT systems are possible due to the frequencies they operate at, typically 10-40kHz, and higher for low power applications. As discussed previously, the power transferred to the pickup is proportional to the operating frequency. At mains frequency (50-60Hz), this is too low, and the magnetics too large to be practical. Invariably, a switch-mode inverter is used to
switch and control the track current in the VLF range, where the frequency is limited only by current switching technology and power levels required [107].

2.5.1 Inverter Configurations

Power supplies can be divided into two main categories; voltage-sourced and current-sourced. Current-sourced IPT supplies are easily identified by the large DC inductor in series with the input voltage [60, 80, 108-114], shown in Figure 2-18(a) and (b). The input current is switched to give a square wave output current, but as the inverter is current sourced, care must be taken to ensure a continuous conductive path. The half-bridge configuration replaces the top switched with a centre-tapped inductor, where the windings are tightly coupled.

Voltage-sourced IPT supplies remove the need for the large DC inductor [85, 115, 116], as shown in Figure 2-18(c) and (d). The half-bridge converter replaces one pair of switches with DC capacitors sufficiently large to hold one output node essentially constant. As such, this configuration is not commonly used. A common IPT supply configuration uses a voltage-sourced full bridge with an LCL network as presented in the following section.
2.5.2 Operating Frequency

IPT supplies can operate at a constant or variable frequency [117]. Variable frequency controllers adjust the frequency such that the VAR loading on the inverter is minimised. Because of this, early power supplies often employed this controller. The disadvantage is that pickups are tuned for a specific frequency, and the power transferred is greatly reduced when the frequency deviates from this tuned frequency. A further problem with these supplies arises at high loading conditions where there may be more than one stable operating point at different frequencies at which the supply could choose to operate at. The inverter can oscillate between these two stable operating frequencies and this bifurcation usually further reduces the power transfer [6, 65, 117]. For these reasons, modern IPT supplies commonly operate at a fixed frequency, and must be rated for any VAR load applied.

2.5.3 Track Compensation

While it is possible in some applications to power an IPT track directly from the inverter bridge output, the track currents usually desired by most industrial systems would require components with very high ratings. As such, except for very low power systems, the track inductance is compensated with a capacitor to form a resonant circuit in order to reduce the VA rating of the inverter. Parallel compensation can be used with current-sourced inverters, and series compensation with voltage-sourced inverters.

The advantage of a parallel tuned system is that the inverter must only supply the real power used by the load and the losses in the track [6, 88, 118]. The resonant tank also allows the track current to be much larger than the inverter current, further reducing losses in the inverter.

Alternatively, series compensation allows the voltage across the track inductor to be much larger than the driving voltage output from the inverter [15, 109]. This is suitable for applications where a long track must be driven from a low voltage power supply. The disadvantage is that the switches in the inverter must be rated for the full track current.

Recently LCL networks have been used, which allow a voltage-sourced inverter to drive a parallel resonant track [119-123], shown in Figure 2-19. When both inductors are chosen to be equal, the resonant frequency of the network is given by \( \omega_0 = \frac{1}{\sqrt{LC}} \) (where \( L_g \) and \( L_1 \) are designed to be identical).
When operated with a sinusoidal voltage at the resonant frequency, the track current is independent of the load on the track:

$$I_1 = \frac{V_0}{\omega_0 L}$$

(2.19)

Therefore, the track current can easily be regulated by changing the input voltage to the network, simply by changing the conduction angle of the switches. With a real load on the track, the input impedance of the network is purely real:

$$Z_{IN} = \frac{(\omega_0 L)^2}{Z_r}$$

(2.20)

Furthermore, the LCL compensation also acts as an impedance conversion network (2.20). A capacitive load on the track appears as an inductive load to the inverter. This is examined later in the thesis when considering the VAR loading presented to the track by a pickup.

2.6 Conclusion

An IPT system consists of two largely independent halves; the primary track and the secondary pickup. The primary contains an inverter, track inductance and a compensation network. The secondary pickup can be broken down into the pickup magnetic, tuning network and controller. Furthermore, IPT systems can be classified as lumped or distributed systems, based on the intended use and the layout of the primary track. This thesis primarily examines a pickup design for distributed AGV systems, with one chapter on distributed monorail systems.

As such, the focus of this chapter is on pickup design. Standard coupling models for IPT systems are presented, along with a new magnetic coupling efficiency metric used to evaluate pickup designs for distributed IPT systems separate from the primary track inductance. A number of tuning and control topologies for pickups are also presented. While the primary and secondary can largely be designed in isolation, the pickup will have some impact on the track and inverter. This is an important aspect when designing pickups for AGV systems, and must be considered.
3 AGV Pickups with Improved Lateral Tolerance

3.1 Introduction

In this chapter, quadrature pickups are introduced as a method for overcoming the limited tolerance to horizontal movement of a pickup across a single phase track. Roadway applications using IPT systems to deliver power to a moving vehicle demand considerably larger lateral tolerance to movement over the track compared with traditional commercial applications. Traditional pickups capture either the vertical or horizontal magnetic field component around a track. Consequently, they suffer from a limited range of movement before the power from these pickups falls to unacceptable levels, at the null points in the individual magnetic field profiles.

Various systems have been proposed to overcome the restrictions in lateral tolerance. Typically these involve complicated track layouts, such as honeycomb or multi-phase track configurations. This considerably complicates the IPT system while also adding cost. In contrast, the primary goal of the quadrature pickup is to provide a simple pickup design that offers increased lateral tolerance to a variety of track systems without significant cost penalty.

This chapter begins by defining the theory of operation of the quadrature pickup in terms of the magnetic design, and the circuit properties that allow the use of such a pickup. Two designs are then presented. One of these designs is then further developed. The pickup design is considered from a purely magnetic viewpoint, with tuning and control, and any impact on the track is largely ignored (in later chapters, the tuning and its effects on the track and pickup will be considered in detail). The focus of this chapter is the improvement of a commercial pickup commonly used for AGV’s in industrial plants. This design is suited for the most commonly used track configuration in industry – a single phase bipolar track. Alternative track configurations are however examined in Chapter Five.

The development of the pickup considers the practical aspects related to the application of vehicle systems. The effect of height and the clearance between the track and pickup on the
pickup design are also investigated. Further modifications are presented to balance the contributions of the pickup coils and increase the lateral tolerance of the pickup, while also considering the cost of the pickup.

### 3.2 Theory of Operation

Since IPT systems use magnetic fields to transfer power from the track to a pickup, it is appropriate to consider first the magnetic field around the track without the pickup present. This can then be used to help inform the design of a suitable pickup.

The field at a point of space around a section of wire is described by the Biot-Savart law, given a steady current flowing in a differential length. In the case of a distributed IPT system, the track length is much greater than the length of the pickup and the offset it operates at, and for this analysis it can be treated as infinitely long. With this condition, the Biot-Savart law simplifies to (3.1), and gives the magnetic flux at a point \((x, y)\) for a track conductor in the \(z\) direction located at \((x_0, y_0)\).

\[
B(x, y) = \frac{\mu_0 I}{2\pi r} = \frac{\mu_0 I}{2\pi \sqrt{(x-x_0)^2 + (y-y_0)^2}} \tag{3.1}
\]

However, it is often useful to consider the horizontal and vertical components of the flux individually. Rewriting (3.1) for the individual components gives:

\[
B_x(x, y) = B \cos \theta = \frac{\mu_0 I}{2\pi \sqrt{(x-x_0)^2 + (y-y_0)^2}} \cos \left(\tan^{-1}\left(\frac{y-y_0}{x-x_0}\right)\right)
\]

\[
B_y(x, y) = B \sin \theta = \frac{\mu_0 I}{2\pi \sqrt{(x-x_0)^2 + (y-y_0)^2}} \sin \left(\tan^{-1}\left(\frac{y-y_0}{x-x_0}\right)\right) \tag{3.2}
\]

IPT tracks typically use a bipolar arrangement, as this provides a natural return for the current. Therefore, the combined magnetic fields of both track conductors need to be considered. This is described in the vector diagram in Figure 3-1. As IPT systems operate at or near resonance, the track currents are almost purely sinusoidal. The current in (3.2) can be treated as such, taking into account the phase of each track conductor. The magnetic flux from each conductor can then be summed to give the overall magnetic field surrounding the track [24]. Using these techniques, a magnetic flux profile 30mm above the track is given in
Chapter 3  AGV Pickups with Improved Lateral Tolerance

Figure 3-2. The track comprises two ideal wires (point sources) spaced at 100mm, with a current of 125A in each wire. From these magnetic flux plots, it can be seen that the horizontal component is at a maximum directly above the track conductors, and drops to zero at a point directly centred between the wires. The vertical flux component is at a maximum at this point.

Figure 3-1: Magnetic field vectors at various positions above a bipolar track.

Figure 3-2: RMS Magnetic flux density at 30mm over a single phase bipolar track.

Traditional IPT pickups for vehicle systems have one coil, and capture only one of the magnetic flux components. Such pickups are presented below, showing a flat pickup in Figure 3-3(a) which captures the horizontal magnetic flux component ($B_x$), and the Flat-E pickup in Figure 3-3(b) which captures the vertical magnetic flux component ($B_y$). Noting that the horizontal field is at a maxima when the vertical component is at a minima, and vice
versa, indicates that a pickup that captures both directional flux components is preferable. By capturing both flux components, the pickup would not be sensitive to the null points in the individual fields, and would be able to deliver power over a greater offset range.

Figure 3-3: Standard IPT pickups (a) a flat pickup for horizontal magnetic field coupling, (b) Flat-E pickup for vertical magnetic field coupling

3.2.1 Structure

To capture both horizontal and vertical components of the magnetic field, a minimum of two coils are required. More may be used, but must be connected in such a fashion as to form two effective coils. A third effective coil can be added to capture the magnetic field in the z direction. This may be desirable on lumped IPT systems, or on a distributed IPT system where the pickup is free to rotate around a vertical axis (skew). This thesis focuses on distributed systems, where the pickup is aligned with the track, so that skew can be ignored. As the application of this pickup is for vehicle systems, a clearance must exist between the pickup structure and the track conductors. A relatively slim design for mounting on the underside of vehicles is also desired. The simplest design for a quadrature pickup combines the horizontal coil of a flat pickup with the flat-E vertical pickup.
Figure 3-4: A quadrature pickup

One of the key properties of the quadrature pickup is that no mutual coupling exists between the coils of each axis. In a case where multiple coils are combined to capture the magnetic field in one direction, the combination of coils must not be mutually coupled with other effective coils.

3.2.2 Circuit

The tuning and control of a quadrature pickup is relatively simple, and requires only minor changes to standard IPT controllers. As the coils of the quadrature pickup have no mutual coupling between them, each coil operates independently. One method of control is to tune each coil, and have a separate rectifier and controller for each coil. The DC output of each controller can then be paralleled. This is a costly solution, as the number of components is doubled, and each controller has to be rated for the full power of each coil.

A more cost effective solution is to individually tune and rectify each coil. The output of the rectifiers are then connected in parallel, and controlled using a single controller. The components in the controller will need to be rated for the full power of the combined coils, approximately 1.5 times that of a single coil. Such a pickup controller is shown in Figure 3-5, in this case, with parallel tuned coils and a current sourced “boost” mode decoupling controller as commonly used in many IPT systems [6, 87].
3.3 Quadrature Designs

To investigate the concept of the quadrature pickup, two designs are compared. The first of these is the simplest design, adding a horizontal coil to the existing ferrite. This design allows easy modification to existing pickups, but does have the disadvantage that the horizontal coil must necessarily extend beyond the ferrite, reducing the clearance between the track the pickup. This is investigated in a later section. The configuration of the windings and the circuit to control the pickup are presented in Figure 3-6.

The second conceptual design for the quadrature pickup consists of two split windings to capture both the horizontal and vertical components of flux surrounding the track. Half of each winding is wound on the left and the right side of the ferrite structure as shown in Figure 3-7(a). It is the interconnection of these half coils and their phase which determines the flux captured by the coil. By connecting the two halves in phase, the winding captures the horizontal flux component, and connecting them out of phase captures the vertical component. Whilst it may be possible to use the two halves for each winding with switching
circuitry to alter the phase, this investigation used two interleaved windings connected as shown in Figure 3-7(b).

One advantage this design offers over the first design presented is that it can be implemented on both the flat-e ferrite and flat ferrite bars, the latter offering a cost advantage. However, to allow fair comparison against the previous design, the pickup was implemented on the same ferrite as specified in Figure 3-8.

![Figure 3-7: Split winding pickup design (a) and an appropriate controller (b).](image)

### 3.3.1 Results

In order to validate the concept of the quadrature pickup, and to assess the two designs presented, small scale prototypes of the two pickups were constructed. Both pickups use a flat-E ferrite as used in industrial vertical pickups for AGV’s (samples courtesy of Conductix-Wampfler AG). The ferrite material is N87 Siferrit from Epcos, with the dimensions of each ferrite half presented in Figure 3-8. For these prototypes, the length of the pickup was kept to one ferrite length (50mm). The coils were wound using light hookup wire (0.3mm² conductor, 1.2mm Dia. including insulation) as indicated previously (Figure 3-6(a) and Figure 3-7(a)). The number of turns for these coils are given in Table 3-1. Two variations of the split winding pickup were investigated to compare against the quadrature pickup; the first variation attempts to match the number of turns of each winding to that of the quadrature pickup, and the second to match each half coil.
Figure 3-8: Wampfler ferrite dimensions

Table 3-1: Pickup winding parameters

<table>
<thead>
<tr>
<th>Pickup Shape</th>
<th>Turns</th>
<th>Inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrature</td>
<td>$N_{2H}$</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>$N_{2V}$</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$L_{2H}$ 60µH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$L_{2V}$ 67µH</td>
</tr>
<tr>
<td>Split Winding</td>
<td>$N_{2H-A}$, $N_{2H-B}$</td>
<td>8 each</td>
</tr>
<tr>
<td></td>
<td>$N_{2V-A}$, $N_{2V-B}$</td>
<td>8 each</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$L_{2H-A} + L_{2H-B}$ 39.3µH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$L_{2V-A} + L_{2V-B}$ 25.7µH</td>
</tr>
<tr>
<td>Split Winding</td>
<td>$N_{2H-A}$, $N_{2H-B}$</td>
<td>15 each</td>
</tr>
<tr>
<td></td>
<td>$N_{2V-A}$, $N_{2V-B}$</td>
<td>15 each</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$L_{2H-A} + L_{2H-B}$ 147.8µH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$L_{2V-A} + L_{2V-B}$ 92.2µH</td>
</tr>
</tbody>
</table>

Each prototype was tested on the same track and power supply setup. For these measurements, this consisted of a single phase bipolar track of 6mm² Litz wire with 93mm track spacing, and with a 10A track current at 38.4kHz. This track spacing was chosen to correspond with the centre of the window area of the ferrite slabs used. The height of the prototype pickups (measured to the bottom of the ferrite) was maintained at 20mm which is typical for industrial AGV’s (10-20mm).

The two prototypes were also simulated using the JMAG electromagnetic modelling software discussed previously in Chapter Two. These simulations are compared to the practical measurements to confirm the accuracy of the simulations. This is necessary as modification of the ferrite is prohibitively costly and difficult, so further investigations must rely on simulated results. Both the simulated and measured results are presented in Figure 3-9. As shown, there is a strong correlation between the simulated and measured results for all the pickups [124]. The variations that do exist, slightly more pronounced in the results of the split
winding coil (Figure 3-9(e-l)), are due to the difficulty in matching the positions of the windings between the physical and computer models. Notably, most of the variation exists due to an asymmetry of the output profiles due to small variations in construction. In the process of obtaining these results, it was found that the dimensions of the coil and the volume of the window area filled can have a pronounced effect on the pickup output. This is further explored in a later section.

The first of the measureable parameters is $V_{oc}$. In a parallel tuned system, this voltage determines the $Q$ required to achieve the desired output voltage. It is also dependant on the number of turns on the pickup. More turns increases the mutual inductance, and from $V_{oc} = j\omega MI_1$, the $V_{oc}$ will also increase. This is evident in the results of Figure 3-9(e) and (i), where the voltage doubles for twice the number of turns on the split winding pickup. As such, the magnitude of $V_{oc}$ is largely irrelevant when comparing pickup magnetic designs. However, the $V_{oc}$ profile over a range of offsets needs to be considered, and is important for the design of the pickup and controller. In the case of these two designs, the maximum points in the $V_{oc}$ profiles for the horizontal windings occur at different offsets. For the quadrature pickup in Figure 3-9(a) it occurs when the pickup is located over the track conductors. For the split winding pickup in Figure 3-9(e) and (i), the maximum point occurs at offsets greater than the track conductors (at ±80mm). At the ±80mm points, one of the half coils is aligned with a track conductor. This is also true for the second measurable parameter, $I_{sc}$, shown in Figure 3-9(f) and (j). This indicates that it is each horizontal half winding that is primarily coupling to the track, and not the combined coil and that the two coils are essentially independent. Also as above, the $I_{sc}$ is dependent on the number of turns used on the pickup, and from $I_{sc} = V_{oc} / j\omega L_2$ the current halves for twice the number of turns, as in Figure 3-9(f) and (j).

Traditionally, when comparing pickup designs it is the uncompensated power, $S_u$, that is used. There are two reasons for this. Firstly, the $S_u$ of a pickup is largely unaffected by the number of turns on a pickup (provided the coupling of the pickup remains unchanged). This is evident in the following equation:

$$S_u = \kappa^2 \left( \frac{N_1}{N_2} \right)^2 I_1^2 \cdot j\omega L_2$$

(3.3)
Provided that the number of turns on the track remains constant and $I_1$ is regulated to be constant, the following relationship can be derived; $S_U \propto \kappa_\phi^2 \frac{L_2}{N_2^2}$, where $L_2 \propto N_2^2$. As such, changing the number of turns $N_2$ has no net effect on $S_U$ unless it changes the coupling efficiency, $\kappa_\phi$. This is confirmed with the results of the split winding pickup in Figure 3-10(g) and (k). Both the 8 turn and 15 turn pickups have identical simulated $S_U$ profiles. By adjusting the number of turns, the $V_{oc}$ and $I_{sc}$ of the pickup can be designed for the desired output current and operating $Q$. The second reason is that the $S_U$ of a pickup largely determines the output power that the pickup can deliver. This is given by $P = Q \cdot S_U$, where $Q$ is typically limited between 1-10.

Notably, the two pickup designs have quite different profiles, due to the coupling of the horizontal coil [124]. The quadrature design has a relatively constant $S_U$, between 0.32 – 0.38VA for offsets within the track conductors (±46mm). With further offset, the $S_U$ drops off almost linearly.

The $S_U$ profile of the split winding pickup in Figure 3-10(g) and (k) varies significantly (0.17 – 0.35VA) with horizontal offset, in comparison to Design 1. This is again due to the maximum point in the horizontal coil occurring at offsets of ±80mm rather than at the ideal null point of the vertical coil at ±46mm. If the desired $S_U$ was low, for example 0.17VA, this pickup design would allow a greater offset range, in this case ±110mm compared to ±90mm for the quadrature pickup. However, the greater $S_U$ of the quadrature pickup is preferable, as a smaller pickup can be used for the same power rating.

Another means for assessing pickups is to compare the coupling to the track. For distributed track systems, $\kappa_\phi$ provides a measure of this coupling independent of the track inductance, and the number of turns of both the track and the pickup. Interestingly, the $\kappa_\phi$ profile of the split winding coil is higher than that of the quadrature pickup. However this improvement does not result from the winding arrangement. As shown later, it arises because the windings of the quadrature pickup do not fill entire window area, whereas in the split winding pickup the windings fill a greater percentage of this window. This is explored in the following section (which focuses solely on the Quadrature pickup).
Figure 3-9: Simulated and measured results showing \( V_{OC} \), \( I_{SC} \), \( S_U \) and \( \kappa_\phi \) profiles respectively (track conductors indicated): (a-d) Design 1; (e-h) Design 2 with 8 turns per split winding; (i-l) 15 turns per split winding.
The final assessment is a comparison of each pickup’s output power [124]. To test this, both pickups were tuned with a parallel tank circuit, and then rectified and controlled using a low power pickup circuit available. This was modified with dual bridge rectifiers for the two coils, and the output was set to 10V DC. An adjustable load was used to find the maximum power available at the various offsets. The results of these tests are presented in Figure 3-10.

From these results it is clear that the quadrature pickup is preferable to the split winding design. Figure 3-10(a) shows that an output power of 1.2W can be maintained over a range of ±90mm, with a variation between 1.2 – 1.8W. In comparison, the split winding pickup can only output half the power, maintaining 0.6W over a range of ±120mm. The variation in output power is also much greater for the split winding pickup as can be predicted from the $I_{sc}$ profiles earlier, given that the voltage can be boosted by $Q$ (but is ultimately fixed at $V_2 = V_{oc}Q = \frac{2\sqrt{2}}{\pi} V_{dc} + 2V_F$), but $I_{sc}$ is limited to that available. For the pickup with 8 turns per split coil in Figure 3-10(b), varies from 0.6 – 1.5W, and for the pickup with 15 turns per split coil the output variation is slightly less – between 0.6 – 1.3W. The quadrature pickup offers higher output power, over a reasonable range, allowing a smaller pickup to be used compared to the split winding pickup.
3.4 Fill Effect

In the previous section, it was noted that the output of the pickups is sensitive to the volume of the window area filled by the coil [124]. To investigate this further, the quadrature pickup of Table 3-1 was simulated with varying coil fills for both the horizontal and vertical coil shown in Figure 3-11, while maintaining the number of turns at the value chosen earlier. The results of this analysis are shown in Figure 3-12.

Figure 3-11: Increasing the coil fill of the window area.

Figure 3-12: Increasing the coil fill of window area (a) $V_{OC}$, (b) $I_{SC}$, (c) $S_U$, (d) $\kappa_{\phi}$.
The coil fill factor only has a minor effect on the \( V_{oc} \) as shown in Figure 3-12(a). Given \( V_{oc} = j\omega M I_1 \), the only parameter that can change is the mutual inductance, \( M \), showing a small increase in the central region of the profile (0.99\( \mu \)H to 1.15\( \mu \)H). Beyond \( \pm 40 \)mm, there is no change in \( M \). However, Figure 3-12(b) shows the \( I_{sc} \) is increased by 35% when the window area is filled, partially because the mutual coupling is increased, but primarily due to a reduction in the pickup inductance, \( L_2 \). This change is also reflected in the \( \kappa_{\phi} \) profile of Figure 3-12(d).

Given the increase in both \( V_{oc} \) and \( I_{sc} \), the increase in \( S_U \) shown in Figure 3-12(c) is expected. Increasing the fill factor of the window area has a greater effect on the vertical coil. The resultant \( S_U \) profile shows a 50% increase when the pickup is centred on the track. It is clearly advantageous to fill all the window area of the pickup. For a practical pickup, this would be realised by using multiple strands of wire in parallel.

### 3.5 Raised Pickup

One of the disadvantages of the quadrature pickup design (as presented) over traditional Flat-E vertical designs is that the added horizontal coil increases the thickness of the pickup. The impact of this depends on the imposed practical limitations of the pickup. Keeping the height of the pickup above the track constant (measured relative to the pickup ferrite) results in a reduced clearance between the bottom of the pickup and the track conductors due to the added winding thickness. However, in practical IPT installations, the clearance between the bottom of the pickup and the track conductors is typically the limiting factor when designing the pickup height. As the coupling of the pickups is very dependent on the height of the pickup [124], a comparison between a standard Flat-E pickup and the quadrature pickup which is raised to give identical clearances to that of the Flat-E is presented in Figure 3-13.

In this case, the change in height was small, only 1.2\( \)mm, due to the use of thin hookup wire. Correspondingly, the change in \( V_{oc} \) and \( I_{sc} \) is also small. When the pickup is centred over the track, the \( V_{oc} \) of the raised quadrature pickup is 4% lower than that of the vertical pickup, as shown in Figure 3-13(a). As expected, the increase in height above the track reduces the mutual inductance. Because the pickup inductance does not change, the short circuit current also reduces by 4%, as does \( \kappa_{\phi} \), shown in Figure 3-13(b) and (d) respectively. The result of this is a relatively significant 8% reduction in \( S_U \) shown in Figure 3-13(c).
Using the controller already discussed, the DC output power of the raised pickup was also measured. Figure 3-14 shows the result of this. Comparing the raised quadrature pickup with a vertical only pickup with both centred on the track results in a 30% decrease in power in the quadrature pickup due to the extra height. However, beyond a 10mm offset the output of the quadrature pickup exceeds that of the vertical pickup, and can maintain that power level for offsets up to 80mm.

![Figure 3-13: Simulated results for a raised quadrature pickup compared to a vertical pickup (a) $V_{OC}$, (b) $I_{SC}$, (c) $S_U$, (d) $\kappa_\phi$.](image)

However, the addition of a quadrature coil as implemented here represents a substantial loss in the available power when the pickup is centred on the track. This power loss is much worse than the results of Figure 3-14 indicate, since practical pickups use heavier gauge wire than the light hookup wire used on this prototype. To assess the true impact that the increased height has on the output of the pickup, a prototype that closely matches those found in industry must be used. Such a pickup is described in the following section.
3.6 Flush Quadrature

In the previous section, it was found that the simulations were very dependent on the coil geometry, primarily the fill of the winding and the diameter of the wire. To effectively assess the quadrature design and any improvements, the prototype must closely resemble existing commercial designs.

The design chosen as the standard for comparison is the IPT®-Floor F-Pickup produced by Conductix-Wampfler AG [125]. These use the ferrites presented in Section 3.3.1 and Figure 3-8. Conductix-Wampfler AG offer pickups ranging from 4 to 10 ferrite slabs in length, with a resultant linear increase in power. To operate at a reasonable power level (approximately 700W), the new prototype pickup is set to be 4 slabs in length (200mm). The winding in the F-Pickups uses $120 \times \text{AWG 32 (0.2mm dia.) strand Rupalit Litz Wire}$ from Pack Feindrähte, with an overall diameter of 3mm. Identical wire was used for both coils on the prototype pickup (wire and ferrite samples courtesy of Conductix-Wampfler AG). The window area was completely filled, resulting in 30 turns for the vertical coil, and 39 turns for the horizontal coil. These pickups are designed to operate with a track current of 125A at 20kHz. The track consists of 8mm diameter Litz wire ($35mm^2$) at a track spacing of 100mm. These conditions are summarised in Table 3-2. Only simulated results are presented in this section as the purpose is to investigate possible alterations to the ferrite prototype. However, these simulations are designed to closely match the constructed prototype in the next chapter.
Table 3-2: Simulation Conditions

<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track Current</td>
<td>Pickup Ferrite</td>
</tr>
<tr>
<td>125A</td>
<td>4 x 2</td>
</tr>
<tr>
<td>(See Figure 3-8)</td>
<td>200mm</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>Horizontal Turns</td>
</tr>
<tr>
<td>20kHz</td>
<td>39</td>
</tr>
<tr>
<td>Track Spacing</td>
<td>Vertical Turns</td>
</tr>
<tr>
<td>100mm</td>
<td>30</td>
</tr>
<tr>
<td>Track Diameter</td>
<td>Pickup Height</td>
</tr>
<tr>
<td>8mm</td>
<td>20mm (unless stated)</td>
</tr>
</tbody>
</table>

As mentioned previously, the added horizontal coil adds volume to the overall pickup dimensions, and effectively reduces clearance between the pickup and the track. To overcome the issue of the reduced clearance, the ferrite needs to be redesigned to allow better integration of the horizontal winding. One such design is to recess the winding into the ferrite [126, 127]. Such a design is shown in Figure 3-15.

![Figure 3-15: Cross section of the proposed flush quadrature pickup.](image)

To assess the impact of this new design, it is compared against two other pickups. Firstly to a pickup having the same dimensions as the prototype without the recessed window area, raised 6mm (2 winding layers) to give an identical clearance. Secondly, to a vertical F-pickup 4 ferrite slabs long. The flush quadrature prototype is simulated with both 3mm and 6mm recesses, corresponding to possible inclusions of either a single or a double layer horizontal winding. The results of these simulations are shown in Figure 3-16.

As shown, the flush quadrature pickup is a substantial improvement over the raised quadrature pickup. Figure 3-16(a) shows a small improvement in the $V_{OC}$ for the flush quadrature design over the raised quadrature pickup, corresponding to a higher mutual inductance. However when compared to the vertical F-pickup, it can be seen that the recess in the ferrite does reduce the $M$ of the pickup when centred on the track, where only the vertical coil contributes to the output. However, from Figure 3-16(b) and (d) it can be seen that the pickup self inductance, $L_2$, reduces linearly with $M$, resulting in an identical $I_{SC}$ and $\kappa_\phi$ at this point. As expected, the raised quadrature pickup is lower for both of these outputs.
Using the $\kappa_\phi$ profiles, pickups of different power levels can be compared. When the flush pickups of Figure 3-16(d) are compared with the original quadrature pickup at the same height (with 100% fill as in Figure 3-12(d)), it is notable that the recess in the ferrite does not have a significant impact on the coupling of the pickup. From (3.3), the reduction of $I_2$ due to the removal of ferrite does lead to a reduced $S_U$ when compared to the F-Pickup centred on the track, and shown in Figure 3-16(c). Also shown is that both flush quadrature designs offer a significant advantage over the raised quadrature pickup. An interesting observation from the $S_U$ profile is that there is effectively no difference in the $S_U$ between the 3mm and 6mm flush quadrature pickup designs, indicating both designs have similar coupling and inductance.
Another factor that needs to be considered when designing the quadrature pickup is the flux density in the ferrite. While the ferrite thickness used in the commercial F-Pickups is easily capable of operating with the flux density normally used in a vertical pickup without approaching saturation, the added horizontal winding will change the flux density, especially when both coils are contributing to the output power. Combined with the removal of ferrite to accommodate the horizontal winding in the flush quadrature design, the resultant flux density may be beyond the capabilities of the ferrite. Of particular concern are localised areas of high flux density.

The analysis of the flux density within the pickup is made possible using computer simulation. The pickups are modelled with the coils open circuit, as this corresponds to the maximum flux in an uncompensated pickup. In a tuned pickup delivering power, the flux will be higher. However this is also highly dependent on the tuning topology used, and the operating Q of the pickup and therefore the flux density under power delivery will be further investigated in the following chapter. However if the flux is well within saturation limits under short circuit operation or open circuit this indicates that it should be possible to proceed with the design in practice.

Figure 3-17 shows the peak flux density on a cross section of the quadrature pickup designs centred on the track. The quadrature design without the recessed coil in Figure 3-17(a) is typical of a commercial F-pickup, as no flux is captured by the horizontal coil at this offset. Here the flux is concentrated above the window area for the vertical coil, with a flux density of 12mT and small areas at 15mT near the corners of the window area. Recessing the horizontal coil in the flush quadrature design narrows down the ferrite between the vertical and horizontal window areas, where the flux density is highest. However, the coupling of the pickup is lower here. The result of this is that the flux density above the vertical window is reduced to 8mT for both the 3mm and 6mm flush quadrature pickups, but reaches 13mT and 20mT respectively where the ferrite narrows due to the recessed horizontal winding, shown in Figure 3-17(b) and (c). For all three designs, the central region of the ferrite has a very low flux density when the pickup is centred on the track, and the flux lines are orientated vertically. Because of this, any imperfections in the joint between the two ferrite halves is not critical, simplifying construction of vertical F-pickups.
However when the pickup is offset as shown in Figure 3-18, the impact of the joint is more pronounced. Here both the 3mm and 6mm flush quadrature pickups are simulated at three specific offsets. The first two are at points where either only the vertical component (0mm) or the horizontal component (60mm) of the flux is captured. The third point is where both components of the flux are captured equally (30mm). For the 3mm recess, at 30mm the flux density in the central limb of the pickup reaches 8mT, and at 60mm it reaches 10mT, shown in Figure 3-18(b) and (c) respectively. At 0mm offset, the flux density in the central limb is negligible at 2 to 4mT for both pickup designs (Figure 3-18a and d). The flux density at the narrow point in the ferrite between the vertical and horizontal window areas is highest when the pickup is offset by 30mm, at 16mT, with a small area at 18mT. With a 6mm recess for the horizontal winding, the flux density increases. Due to the lower volume of ferrite, the flux density in the central limb is 14mT and 16mT at 30mm and 60mm offsets respectively, as
shown in Figure 3-18(e) and (f). A concern is the flux density at the narrowest point in the ferrite, reaching 20mT at all offsets shown, particularly at 30mm and 60mm offsets.

![Figure 3-18: Detailed peak flux density of the quadrature flush pickup for the 3mm recess at (a) 0mm, (b) 30mm, (c) 60mm, and the 6mm recess at (d) 0mm, (e) 30mm, (f) 60mm.](image)

From these results it can be seen that while the 3mm and 6mm flush quadrature pickups may produce similar outputs, the 6mm design less desirable when the flux density of the pickup is considered. The 3mm design has a relatively uniform flux density, with only a small concentration of flux at the corner of the vertical coil window area. With a small bevel or fillet on the edges of the window areas, a substantial reduction in this flux density concentration can be achieved with little impact on the winding area.

### 3.7 Pickup Height

In the previous section, the effect of the location of the quadrature winding on the pickup and its impact on pickup height relative to the track (as required to maintain a ground clearance identical to a commercial vertical only F-Pickup) was briefly considered. As expected from previous research [16, 24], increasing the height decreased the coupling and uncompensated power of the pickup. However, the quadrature pickup differs from previously researched pickups by having two coils. It is commonly understood that pickups capturing the vertical flux component are more sensitive to height compared with those capturing the
horizontal component. Consequently, the balance in output of the two coils on the quadrature pickup is dependent on height. To investigate this dependence, the newly proposed flush quadrature pickup was simulated with a height of 10mm to 70mm. The output profiles at these heights are shown in Figure 3-19. However, to assess how the outputs of each coil on the quadrature pickup change with height, the maximum output from each coil is plotted against height in Figure 3-20. A fitted exponential trend line provides an indication to the rates of change in the outputs of the coils in relation to height.

Figure 3-19: Simulated results of the flush quadrature pickup at various heights above the track (a) \( V_{OC} \), (b) \( I_{SC} \), (c) \( S_U \), (d) \( \kappa_\phi \).

From the \( V_{OC} \) profile shown in Figure 3-19(a) it can be seen that the balance between the two coils does change with height. As the pickup height increases, the \( V_{OC} \) profile flattens, but is much reduced. Looking at the maximum \( V_{OC} \) for each coil at the various heights shown in Figure 3-20(a), there is an almost exponential drop in \( V_{OC} \) with height increase for both
coils. These results are approximated with exponential curves of best fit as shown, from which it is noted here that the $V_{OC}$ of the vertical coil decreases at 1.4 times the rate of the $V_{OC}$ of the horizontal coil with a change in pickup height. The graph also shows that at 30mm height, the $V_{OC}$ and hence the mutual inductance of the two coils is balanced.

![Graphs showing the change of vertical and horizontal components with pickup height.](image)

**Figure 3-20:** Change of vertical and horizontal components with pickup height, (a) $V_{OC}$, (b) $I_{SC}$, (c) $S_U$, (d) $\kappa_\phi$

As the inductance of the pickup does not change, nor does the number of turns, the $I_{SC}$ and $\kappa_\phi$ profiles in Figure 3-19(b) and (d) change at the same rate as the $V_{OC}$ profile. This is confirmed with the approximated curves in Figure 3-20(b) and (d). However, the $I_{SC}$ of the two coils do not quite balance, and from the plotted trend this balance will likely result at a height of 90mm. The coupling of the two coils shown in Figure 3-20(d) are balanced at a pickup height of 70mm, which corresponds with the height where the $S_U$ of the two coils are balanced.
also balanced in Figure 3-20(c). As \( S_U \) is the product of \( V_{OC} \) and \( I_{SC} \), the relative decrease in \( S_U \) with height is double, as shown.

These results show that the vertical coil is more sensitive to height than the horizontal coil. However, they balance at quite a large pickup height above the track, where the output from the pickup is low. Because of this, it is not feasible to try and balance the coil contributions by varying height. Consequently the following section considers changes to the ferrite shape to improve the balance between these outputs. These investigations will be carried out at a pickup height of 20mm, which is typical of commercial F-Pickups.

### 3.8 Balancing Coil Output

One of the problems noted earlier is that the contributions of each coil to the overall power profile is often not balanced. This is especially the case when retrofitting the quadrature coils onto ferrite used in standard commercial pickups, as these are optimised to capture vertical flux. To improve the balance between these contributions, various modifications to the magnetic structure are presented here with the associated power profiles. These modifications focus on lengthening the magnetic structure, as this is a common method of increasing coupling on flat bar pickups [24]. While a balanced \( S_U \) profile is desired, it is also necessary to balance the Dominant Electrical Parameter (DEP). For series tuned pickups this is the \( V_{OC} \), and for parallel tuned pickups is the \( I_{SC} \). The other parameter is tuned up (within reasonable limits) to the regulated voltage or current. The effectiveness of the proposed designs shown below in Table 3-3 are assessed against the added volume of ferrite as a reflection on the cost of the ferrite. While the complexity of the ferrite shape will have some bearing on the cost of manufacture, this is primarily in set up costs, and as such (given sufficient production volumes), this additional cost becomes negligible.
Table 3-3: Pickup extensions to improve coil balance

<table>
<thead>
<tr>
<th>Pickup Shape</th>
<th>Track Space</th>
<th>Extension</th>
<th>Volume ferrite c.f. Original</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wings</td>
<td>100mm</td>
<td>10mm</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>100mm</td>
<td>20mm</td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td>100mm</td>
<td>30mm</td>
<td>94%</td>
</tr>
<tr>
<td></td>
<td>100mm</td>
<td>40mm</td>
<td>102%</td>
</tr>
<tr>
<td>End Extensions</td>
<td>100mm</td>
<td>10mm</td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td>100mm</td>
<td>20mm</td>
<td>102%</td>
</tr>
<tr>
<td></td>
<td>100mm</td>
<td>30mm</td>
<td>120%</td>
</tr>
<tr>
<td></td>
<td>100mm</td>
<td>40mm</td>
<td>138%</td>
</tr>
<tr>
<td>Centre Extension</td>
<td>100mm</td>
<td>10mm</td>
<td>74%</td>
</tr>
<tr>
<td></td>
<td>100mm</td>
<td>20mm</td>
<td>81%</td>
</tr>
<tr>
<td></td>
<td>100mm</td>
<td>30mm</td>
<td>88%</td>
</tr>
<tr>
<td></td>
<td>100mm</td>
<td>40mm</td>
<td>95%</td>
</tr>
<tr>
<td>Centre Extension with Track</td>
<td>120mm</td>
<td>10mm</td>
<td>74%</td>
</tr>
<tr>
<td></td>
<td>140mm</td>
<td>20mm</td>
<td>81%</td>
</tr>
<tr>
<td></td>
<td>160mm</td>
<td>30mm</td>
<td>88%</td>
</tr>
</tbody>
</table>

3.8.1 Extensions

3.8.1.1 Wings

The first modification is the addition of wings to the sides of the ferrite (Table 3-3), which effectively lengthens the magnetic structure to improve the capture of flux. This is commonly applied to standard vertical F-Pickups to increase the power when centred on the track [126].

3.8.1.2 End Extensions

A similar modification to the addition of wings is extending the ends of the ferrite (Table 3-3). Again this lengthens the magnetic structure; however, twice the ferrite is used for the extension. Whether this has an impact is determined in the following results.

3.8.1.3 Centre Extension

Another means of lengthening the magnetic structure is to extend the middle section of the ferrite (Table 3-3). This has the added advantage of increasing the winding area for the horizontal coil, thereby containing the flux within a greater volume of ferrite. The added ferrite volume is dependent on the depth of the recess for the horizontal winding. From the results of the previous section, a 3mm recess was chosen as the preferred option. A further option is
to increase the track width along with the pickup, so that the vertical winding remains aligned with the track conductors [126].

3.8.2 Results

All of the pickup modifications extend the lateral range of the pickup to an extent. However, some adversely affect the output when the pickup is centred on the track, and others do not balance the contributions of the vertical and horizontal coils. To investigate this, each of the new pickup design outputs are compared.

3.8.2.1 Open Circuit Voltage

Figure 3-21 shows the $V_{oc}$ profiles for each pickup design. The results observed with the addition of wings and with added extensions at the ends of the flush quadrature pickup (shown in Figure 3-21(a) and (b)) appear very similar. Both extend the magnetic path for the horizontal winding, with the wing extensions using half the ferrite of the extended ends to achieve the same result. These extensions primarily increase the $V_{oc}$ profile for offsets beyond the track conductors ($\pm$50mm). The extensions only have a small effect on the vertical contribution of the pickup, resulting in lower gains for offsets less that 50mm, which help balance the $V_{oc}$ profile. With a 40mm extension, both the maximum and minimum points of the profile are equal. A $V_{oc}$ of 100V can be maintained over a range of $\pm$120mm offset, with a ripple of 20%. This is an improvement over the original pickup, which maintains 90V over a range of $\pm$100mm with a 25% ripple.

Extending the centre of the ferrite also lengthens the magnetic path for the horizontal winding, coupling the horizontal flux component over a larger range of offsets. This results in the wider $V_{oc}$ profile shown in Figure 3-21(c). However, an extension greater than 10mm provides a path for the vertical flux component through the ferrite and does not cut the vertical coil, resulting in a lower coupling. This results in a lower $V_{oc}$ for pickup offsets less that 50mm. A 40mm extension allows a $V_{oc}$ of 80V to be maintained over a range greater than $\pm$150mm. This voltage is lower than the original, but the range is 50% greater.

When the track width is increased along with the extension as shown in Figure 3-21(d), the vertical flux path through the ferrite that avoids the vertical coil does not exist. Also, the extended $V_{oc}$ profile due to the horizontal winding from the previous model is unchanged, except now the track conductors are spaced further apart, resulting in a sustained output
over an increased offset. As shown, the $V_{OC}$ is higher over the entire profile. A 40mm extension, along with a track spacing of 180mm, allows 100V to be maintained up to an estimated range of $\pm200$mm, with a ripple of 30%. A smaller extension of 20mm allows the same voltage to be maintained between $\pm150$mm. From these extension designs, the wing extensions provide the best balance of $V_{OC}$ between the vertical and horizontal coil. However, while the centre extension with an increased track width does not balance the $V_{OC}$ of the coils as effectively, the $V_{OC}$ is higher for all offsets, and the range of the pickup across the track is doubled.

### 3.8.2.2 Short Circuit Current

The $I_{SC}$ achieved with the wing and end extensions (shown in Figure 3-22(a) and (b)) are very similar, indicating that the added inductance of both extensions is similar despite the extra volume of ferrite in the end extension design when compared to the wing extensions. The total change in $I_{SC}$ due to the extensions is minimal and therefore it is expected that $\kappa_\phi$ will remain largely constant, although there is a small improvement at offsets greater than 70mm. This does result in a small increase in range over which current can be maintained – above 1A in the modelled prototype, resulting in an increase of 10mm offset from centre.

Similar to the $V_{OC}$ profile of Figure 3-21(c), Figure 3-22(c) shows that the addition of a centre extension to the pickup extends the offset range where the $I_{SC}$ can be maintained and provides a better balance between the contributions of the vertical and horizontal coils. However, this balance is due to the reduction of the vertical contribution from the flux path in the ferrite not passing through the vertical coil. This reduces the overall $I_{SC}$ profile between the track conductors ($\pm50$mm). With a 40mm extension, a 1A current is maintained over an offset range of $\pm150$mm.

Extending the spacing of the track along with the centre extension of the ferrite as shown in Figure 3-22 provides the best improvements. The $I_{SC}$ of the pickup when centred on the track remains unchanged. For all other offsets, the extension increases the short circuit current, with the benefit of also extending the range over which the $I_{SC}$ can be maintained.

For a 40mm extension on a track of 180mm, 1.4A can be delivered over an estimated range of $\pm200$mm (a 40% improvement in current over an offset which is increased by more than 400%).
3.8.2.3 Uncompensated Power

While the wing and end extensions balance the coil contributions of $V_{OC}$, they do not have the same effect on the resulting $S_U$ profile. Figure 3-23(a) and (b) show the increase in $S_U$ due to the extensions that occur when the pickup is centred on the track, and at offsets beyond 70mm. At offsets of $\pm 50$mm, the $S_U$ is largely unchanged, indicating little improvement in the horizontal component. The extensions do allow an increased offset range, with a 40mm extension capable of delivering 80VA over a range between $\pm 110$mm, which is an improvement over a range of $\pm 60$mm without the extensions.

Extending the centre of the ferrite does balance the contributions of the vertical and horizontal coils to the $V_{OC}$ and $I_{SC}$ profiles. However, this is achieved through a reduction in output due to the vertical coil, especially with the pickup centred on the track, shown in Figure 3-23(c). This results in an $S_U$ profile where the contributions of each coil are also balanced, and the resultant profile remains relatively flat for a large offset range. At 0mm offset, the $S_U$ is only 60% of that for a pickup without any extension. The extension does extend the range that the pickup can operate over, and with a 40mm extension, this pickup can maintain 80VA over $\pm 130$mm, with a ripple of 40%. The ripple typically exceeds 100% for the other extension designs. However, the reduction in $S_U$ at the centre of the track is undesirable.

The biggest gains arise when the track width is extended along with the centre of the ferrite, as shown in Figure 3-23(d). $S_U$ across the full profile is increased, and the offset range is also improved. Notably the ferrite and track extension has its greater effect on the contribution from the horizontal coil, largely due to the improvements in $I_{SC}$. With a 40mm extension, and a track spacing of 180mm, the pickup can maintain 100VA over a range of $\pm 170$mm. Alternatively, a higher $S_U$ of 130VA can be maintained over a slightly smaller range of $\pm 100$mm, depending on the design criteria required. From these results it is clear that the centre extension, with the associated increase in track spacing is the best means of improving the balance of the coils, while also increasing the $S_U$ and the offset over which the pickup delivers power.
3.8.2.4 Coupling Efficiency

The previous results show which of the extensions give the best outputs. These results stem from the magnetic coupling of the pickup, which is described using $\kappa_\phi$ profiles. Figure 3-24 presents the $\kappa_\phi$ for each of the pickup extensions, with Figure 3-25 and Figure 3-26 showing the $\kappa_\phi$ of the individual horizontal and vertical coils respectively and as expected these largely follow the $I_{SC}$ profiles given the turns ratio remains fixed in the designs.

Both the wing and end extensions have a small effect on the $\kappa_\phi$ of the pickup, primarily at offsets beyond 90mm, as shown in Figure 3-24(a) and (b). These extensions increase the $\kappa_\phi$ of the vertical coil only slightly in Figure 3-25(a) and (b), with a 40mm extension giving a 0.02 increase with the pickup centred, and at offsets beyond 100mm. However, the extensions do widen the $\kappa_\phi$ profile of the horizontal winding in Figure 3-26(a) and (b), increasing the $\kappa_\phi$ at offsets beyond 90mm by approximately 0.03, but with a resulting reduction of 0.02 for offsets of 30mm to 50mm. This results in the small improvements at large offsets seen in the profile combining both coils.

The centre extension of the pickup has a greater impact on the horizontal coil compared to the previous extensions, as seen in Figure 3-25(c). This is due to the horizontal coil covering a much larger area of the ferrite, which from previous research [16] is known to improve the coupling of flat pickups. In this case, the maximum $\kappa_\phi$ is increased by 0.035, and the profile is extended, resulting in improvements of 0.12 at extensions beyond 100mm. However, as previously mentioned, this extension allows a portion of the vertical component of flux to travel through the ferrite without coupling the vertical coil, resulting in the profile in Figure 3-26(c). The reduction in $\kappa_\phi$ due to this flux path is clear for offsets between ±40mm with an extension of 40mm, and results in the decrease of $\kappa_\phi$ in the combined profile of Figure 3-24(c) for offsets of ±40mm. However, with a small extension of 10mm, the vertical $\kappa_\phi$ profile when the pickup is centred is effectively unchanged, while the range of the profile is increased. The result of this is an increase in $S_v$ with the pickup centred as well as offset. Therefore, a 10mm extension is of benefit to both vertical only F-Pickups as well as the quadrature pickup, possibly in combination with wings.

The best results are obtained when the track width is increased along with the centre pickup extension. This minimises the flux path through the ferrite which does not couple with the
vertical winding, resulting in an identical coupling with the pickup centred on the track, as shown in Figure 3-26(d). As the track width has increased, the position of zero coupling shifts as well, resulting in an increased range in the vertical $\kappa_\phi$ profile. The increased track width also benefits the horizontal coil $\kappa_\phi$ profile. As the track conductors are spaced further apart, the horizontal flux components from each conductor do not cancel to the same extent. This results in the $\kappa_\phi$ profile in Figure 3-25(d), with an increased coupling over a greater offset range. This increase in coupling for the horizontal winding is greater than that achieved in the vertical winding, producing the balanced $\kappa_\phi$ profile in Figure 3-24(d). The $\kappa_\phi$ is reasonably constant (between 0.45 – 0.55) over the range simulated, and is estimated to extend to offsets of ±200mm. With the added increase in $L_z$ due to the extension, the $S_U$ is increased over the entire offset range.

3.8.2.5 Volume

Ideally any $S_U$ improvements should be achieved with little or no change to the ferrite volume of the original F-Pickup. This can be achieved by extending the pickup using only the volume of ferrite required to be removed to allow the horizontal coil to be recessed. From Table 3-3, this restricts the extension length to 30mm for the wings, and 40mm for the centre extensions, assuming a 6mm recess for the horizontal coil is used. From the above results the wing design and end extensions are ruled out as an inefficient use of ferrite. With such small extensions, either wings or the centre extension are similar in output, with the $I_{sc}$ profile of the centre extension giving a slight advantage. However, a 20mm wing is commonly used on commercial vertical F-Pickups, thus little change is required. The advantage of the centre extension is that it can also be used on a track with increased width to produce an improved output profile. If the track width can be modified, there is a significant advantage to increasing the centre extension further to improved the balance between the coils, and achieve an increase in offset range.
Figure 3-21: Simulated results showing $V_{OC}$ for (a) wings, (b) end extensions, (c) centre extension, (d) centre extension with track.

Figure 3-22: Simulated results showing $I_{SC}$ for (a) wings, (b) end extensions, (c) centre extension, (d) centre extension with track.
Figure 3-23: Simulated results showing $S_U$ for (a) wings, (b) end extensions, (c) centre extension, (d) centre extension with track.

Figure 3-24: Simulated results showing total $\kappa_\phi$ for (a) wings, (b) end extensions, (c) centre extension, (d) centre extension with track.
Figure 3-25: Simulated results showing horizontal $\kappa_\phi$ for (a) wings, (b) end extensions, (c) centre extension, (d) centre extension with track.

Figure 3-26: Simulated results showing vertical $\kappa_\psi$ for (a) wings, (b) end extensions, (c) centre extension, (d) centre extension with track.
3.9 Conclusions

Pickups in traditional single phase IPT systems have a limited range of movement before the power drops to unacceptable levels. This is because they have been designed to capture only one component of the magnetic field surrounding the track.

Quadrature pickups increase the range of movement possible, by capturing both the vertical and horizontal components of the magnetic field. This can be achieved with windings orientated around x and y axes, or by using a split winding design to achieve the same effect. Both designs were introduced in this chapter, and the former design was fully investigated and further developed while considering its practical application. The clearance between the pickup and track was maintained by recessing the coil into the ferrite, and the resultant increase in flux density was investigated. The ferrite material which is removed to fit the horizontal winding was reintroduced to enhance the pickup structure (without increasing the volume of ferrite used) in order to balance the contributions of each coil and further increase the range over which the quadrature pickup can deliver power. As shown, it is possible to design a modified pickup with 40% improvement in power and with a 400% improved tolerance providing the track separation is widened by 20%, while still keeping the flux density in the pickup well below levels that would saturate the ferrite.
4 Tuning and Control of Quadrature Pickups and System Effects

4.1 Introduction

The previous chapter introduced the concept of the quadrature pickup, and investigated various improvements that can be made magnetically by reshaping the ferrite. As discussed, it is difficult to balance the contribution from each of the coils purely by magnetic design.

This chapter begins by presenting a method to balance the contribution using partial series compensation, allowing the $V_{oc}$ of each coil to be matched. This is compared against a parallel tuned pickup without any series compensation, where the $I_{sc}$ of each coil is matched. The impacts which each tuning topology has on the flux in the pickup, their efficiency, and the impedance of the pickup and tuned circuit reflected back onto the IPT power supply are investigated and compared. The impacts of using alternative series and LCL tuning topologies on pickup flux and reflected impedance are also considered for comparison.

4.2 Partial Series Compensation

In order to improve the lateral range over which the quadrature pickup can deliver sufficient power, the contributions of both the horizontal and vertical flux capturing coils should be balanced. In the previous chapter, magnetic solutions were investigated but despite significant improvements it was notably difficult to balance the flux capture of both windings. Consequentially, some additional electrical compensation is required to overcome this imbalance. As discussed following this can be accommodated by one of two methods, namely balancing output voltage ($V_{oc}$) of the coils or the short circuit current ($I_{sc}$) in each of the coils.

As discussed previously in chapter 3, the maximum $V_{oc}$ of each coil occurs when the pickup is at different offsets, and when one coil is at a maximum, the other coil is at a minimum $V_{oc}$. The same also applies to the $I_{sc}$ of the two coils. To balance the contribution of the two
coils, the maximum $V_{oc}$ or $I_{sc}$ should be matched, whichever is the Dominant Electrical Parameter.

If the coils are wound such that the maximum $I_{sc}$ of each individual coil is equal, the coil that has the lower $V_{oc}$ will be forced to operate at a higher $Q$. In the case of the quadrature pickup described in the previous chapter, the horizontal winding has a maximum $S_U$ approximately half that of the vertical coil. When the coils are wound for equal maximum $I_{sc}$, the horizontal coil operates with a voltage $Q$ twice that of the vertical coil. A pickup operating with a higher $Q$ is more sensitive to component variations, and because of this commercial pickups are typically limited to $Q_F$ below 10.

In order to increase the $I_{sc}$ of the horizontal coil in order to match the vertical coil, the number of turns must be reduced. This can adversely affect the mutual coupling of the horizontal coil with the track if the coil span does not cover the same area of magnetic material. This can be addressed using construction techniques such as bifilar windings, but this complicates the construction of the pickup, given the number of terminations are increased.

The alternative approach is to balance the maximum open circuit voltages and then compensate for the imbalance of the coils by using partial series tuning [92, 127]. This is achieved using a series capacitor to reduce the effective impedance of the pickup coil to increase the current supplied. To apply this to the quadrature pickup, the number of turns on the horizontal coil is chosen so that the peak $V_{oc}$ of the coil (which occurs at 60mm offset from the results in Chapter 3) matches the peak $V_{oc}$ of the vertical coil (when centred on the track). Naturally the inductances of the horizontal and vertical windings differ, with a resulting mismatch in the maximum $I_{sc}$ of each coil. In order to match these, partial series compensation is used on the horizontal coil to boost the peak $I_{sc}$ by adding the series capacitor shown in Figure 4-1, reducing the effective reactance of the horizontal winding. The increase in $I_{sc}$ is quantified by $Q_I$, which is defined as:

$$Q_I = \frac{C_2}{C_{L2}} + 1$$  \hspace{1cm} (4.1)
The overall tuned quality factor, $Q$, of this horizontal winding is given by $Q = Q_I \cdot Q_V$ where $Q_V$ is the required boost in voltage which is commonly set based on the desired regulated output voltage.

![Figure 4-1: Partial series compensation](image)

To balance the peak $I_{SC}$ of both the vertical and horizontal coils on the quadrature pickup of the previous chapter in Section 3.6, a $Q_I = 2$ is required. The resulting partially compensated power profile is shown in Figure 4-2(a), compared against the quadrature pickup without any series compensation, and a vertical pickup with identical clearance. Clearly series compensation is able to balance the contributions of each coil, with an $S_u$ of 150VA maintained over an offset of ±80mm. Due to the available capacitors in the laboratory and a desire to extend the pickup tolerance to misalignment, a $Q_I = 2.25$ was used on the constructed pickup described in the following section.

![Figure 4-2: Uncompensated and partially series compensated power of the Quadrature pickup compared to a standard vertical pickup with; (a) no magnetic improvements ($Q_I = 2$), (b) 40mm centre extension with increased track width ($Q_I = 1.8$).](image)
Ideally, electrical compensation techniques are used in conjunction with magnetic design to increase the range over which quadrature pickups can effectively deliver power. This is shown in Figure 4-2(b), where partial series compensation is applied to the quadrature pickup with a 40mm centre extension with the associated increased track width presented in section 3.8. For this second design, a $Q_i=1.7$ is applied to balance the contributions of the two coils. With this improved pickup, 180VA can be maintained over an offset range of ±140mm. While series compensation is clearly effective, it does influence the performance of the pickup and the IPT system as a whole, and this influence is evaluated in the following sections.

4.3 Pickup Operation

To investigate the operation of the quadrature pickup, a pickup regulator was designed rated for a maximum 1kW using the circuit and commercial ferrite described in the previous chapter. Throughout this chapter comparisons are made between quadrature pickups with a 39 turn horizontal coil and series tuning where the peak $V_{oc}$'s of each coil is matched, and a 19 turn horizontal coil where the peak $I_{sc}$'s of each coil are matched. Later a quadrature pickup with a 16 turn horizontal coil is also considered. The inductances and the required tuning capacitors are listed in Table 4-1.

Partial series compensation is only required for the 39 turn horizontal coil, to boost the peak $I_{sc}$ as described earlier. As this boost applies additional stress on the pickup components, evaluating the impact of this approach is the main focus of this section.

<table>
<thead>
<tr>
<th>Quadrature Horizontal Coil</th>
<th>$L_{2v}$</th>
<th>$C_{2v}$</th>
<th>$L_{2H}$</th>
<th>$C_{2H}$</th>
<th>$C_{L,H}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>39 Turn Horizontal</td>
<td>508.9µH</td>
<td>124nF</td>
<td>698µH</td>
<td>200nF</td>
<td>160nF</td>
</tr>
<tr>
<td>19 Turn Horizontal</td>
<td>508.9µH</td>
<td>124nF</td>
<td>195.6µH</td>
<td>323.7nF</td>
<td>-</td>
</tr>
<tr>
<td>16 Turn Horizontal</td>
<td>508.9µH</td>
<td>124nF</td>
<td>123.7µH</td>
<td>511.9nF</td>
<td>-</td>
</tr>
</tbody>
</table>

The maximum output power of the quadrature pickup with the constructed controller is shown in Figure 4-3. As expected there is a significant improvement in lateral tolerance compared to the maximum output power of the individual pickup coils. Correspondingly, an output power of 400W can easily be maintained over a ±120mm lateral displacement, compared to only ±20mm offset if only the vertical coil is used.

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Figure 4-3: Maximum output power of the quadrature pickup (39 turn horizontal coil)

The quadrature pickup has a unique characteristic when operating compared to traditional pickups. Both coils resonate to full voltage for the majority of offsets. When one of the coils has a low coupling, and therefore a low $V_{OC}$, the other is well coupled with a high $V_{OC}$. The coil with the high $V_{OC}$ provides the majority of the power to the load. When this occurs, the voltage on the DC side of the rectifier is at the output voltage, and the other coil only has to overcome the losses associated with that coil to resonate up to the same voltage. The resonant voltage is given by:

$$V_{Res} = \frac{\pi}{2\sqrt{2}} V_{DC} + 3V_f$$

(4.2)

As the implemented controller regulates the output to 300V, the resonant voltage of each tank circuit is 333V when delivering power.

Table 4-2 and Figure 4-4 show the essential operating conditions of both coils when the quadrature pickup is required to deliver 400W to the load. These results are taken in critical offsets; 0mm where the horizontal coil does not contribute (as here its $V_{OC}$ is too low and the required $Q_f$ is too large to be able to resonate to $V_{Res}$), 5mm where the horizontal coil does not contribute significant power but resonates to full voltage, and 40mm where both coils contribute equally to the power demand. Figure 4-4 shows the resonant voltages and currents of both coils as the decoupling switch of the pickup controller turns off while under hysteresis control (the top two traces relate to the horizontal coil and the lower two to the vertical coil). At 0mm, the $V_{OC}$ of the horizontal winding is near zero. In order to resonate to 333V an overly large $Q_f$ is necessary. The tank circuit effectively sees no load, as full power is provided by the vertical coil. The only limitation to full resonance are the losses and
tolerance of the components in the tank circuit. From Figure 4-4(a) and Table 4-2, this coil requires a $Q_v$ of 65 but has an operating $Q_v$ of 19, which is limited by the component tolerance in the constructed controller.

At 5mm offset (shown in Figure 4-4b) the tuned horizontal coil is able to resonate close to full voltage across $C_{2H}$. Consequentially, when the quadrature pickup is located near 0mm offset, the horizontal winding is simply adding loss since the full resonant current is ringing through the winding and tuning capacitors, unnecessarily reducing the overall efficiency (this is quantified later in Section 4.6). At larger offsets, both coils resonate to full voltage (Figure 4-4c), supplying the losses in each resonant circuit, and also contributing proportionally to the output load.
Figure 4-4: Resonant tank voltage and currents ($V_{Res \_H}$—Yellow, $I_{Res \_H}$—Green, $V_{Res \_V}$—Purple, $I_{Res \_V}$—Pink) at: (a) 0mm Offset (Vertical contribution only); (b) 5mm offset (Horizontal resonating); (c) 40mm offset (Equal contribution).
One important aspect of using series tuning on the horizontal coil is the operating voltages of the horizontal pickup winding and the series tuning capacitor. The coil voltage is substantially higher than pickups operating without partial series tuning. This voltage is proportional to the $Q_i$ applied to the coil. The voltage across the partial series tuning capacitor opposes the winding voltage to produce the required resonant voltage across $C_{2H}$. The operating voltages are described by the following equations:

$$V_{	ext{Coil}} = Q_i \cdot V_{\text{Res}}$$

$$= Q_i \left( \frac{\pi}{2\sqrt{2}} V_{\text{DC}} + 3V_F \right) \quad (4.3)$$

$$V_{c_{22}} = (Q_i - 1) \cdot V_{\text{Res}} \quad (4.4)$$

For the pickup controller described previously, with a $Q_i$ of 2.25 on the horizontal coil, and a resonant voltage of 333V, using (4.3) the coil voltage is expected to be 750V, and from (4.4) the series capacitor voltage will be 417V. These match the measured operating conditions of Table 4-2 when the pickup is located at 40mm and the horizontal coil is operating at full resonance.

**Table 4-2: Measured Operating Conditions.**

<table>
<thead>
<tr>
<th>Pickup Shape</th>
<th>0mm</th>
<th>5mm</th>
<th>40mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical $V_{OC}$</td>
<td>90.1V</td>
<td>88.1V</td>
<td>49.5V</td>
</tr>
<tr>
<td>Vertical Resonant Voltage</td>
<td>343V</td>
<td>344V</td>
<td>330.8V</td>
</tr>
<tr>
<td>Vertical Resonant Current</td>
<td>5.37A</td>
<td>5.36A</td>
<td>5.40A</td>
</tr>
<tr>
<td>Vertical Coil Inductance (20kHz)</td>
<td>508.9µH</td>
<td>508.9µH</td>
<td>508.9µH</td>
</tr>
<tr>
<td>Vertical Coil Resistance (20kHz)</td>
<td>237mΩ</td>
<td>237mΩ</td>
<td>237mΩ</td>
</tr>
<tr>
<td>Horizontal $V_{OC}$</td>
<td>5.08V</td>
<td>14.5V</td>
<td>62.1V</td>
</tr>
<tr>
<td>Horizontal Resonant Voltage</td>
<td>95V</td>
<td>246.3V</td>
<td>337.7V</td>
</tr>
<tr>
<td>Horizontal Resonant Current</td>
<td>1.90A</td>
<td>4.74A</td>
<td>6.40A</td>
</tr>
<tr>
<td>Horizontal Coil Voltage</td>
<td>232V</td>
<td>554V</td>
<td>762V</td>
</tr>
<tr>
<td>Horizontal Series Capacitor Voltage</td>
<td>127.6V</td>
<td>308.9V</td>
<td>427.7V</td>
</tr>
<tr>
<td>Horizontal Coil Inductance (20kHz)</td>
<td>698µH</td>
<td>698µH</td>
<td>698µH</td>
</tr>
<tr>
<td>Horizontal Coil Resistance (20kHz)</td>
<td>239mΩ</td>
<td>239mΩ</td>
<td>239mΩ</td>
</tr>
</tbody>
</table>
Chapter 4  Tuning and Control of Quadrature Pickups and System Effects

The pickup must be designed to withstand these higher operating voltages when series tuning is applied. This is one factor which limits the pickup $Q_i$. If coil voltages below 1kV are desired then for a standard output voltage of 300V, this should be limited to a $Q_i$ below 3, and below 1.5 for an output of 560V. One solution to this which is commonly employed on IPT tracks, and occasionally for high power pickups is to split the coil into smaller inductances, with multiple series capacitors in between these such that the voltages are below difficult or dangerous levels. This would allow greater $Q_i$'s to be used.

4.4 Reflected Impedance

An important consideration when designing IPT pickups is their impact on the whole IPT system and potential changes to the track inductance causing additional VAR loading to the IPT supply [87, 120]. This variation in track inductance occurs for two reasons; firstly, the introduction of pickup ferrite on AGV systems increases the track inductance, and changes as vehicles move on and off the track (in monorail systems the ferrite is always present and is compensated out with track tuning). Secondly, the reflected impedance of the pickup can change the track inductance. This is dependent on the pickup tuning topology used, and from [91, 117] is given by:

$$Z_r = \begin{cases} 
\frac{\omega^2 M^2}{X^2} (R - jX) & \text{parallel tuned} \\
\frac{\omega^2 M^2}{R} & \text{series tuned} \\
\frac{\omega^2 M^2 R}{X^2} & \text{LCL tuned}
\end{cases}$$

(4.5)

Series and LCL tuned topologies both reflect only a real impedance to the track without any added reactance (4.5). For monorail IPT systems, where the pickup inductance can be compensated for within the track tuning, these pickup topologies are ideal. However, in AGV applications where pickups are free to move from the track, the changing track inductance cannot be compensated using track tuning, so that the series and LCL topologies may not be desirable.

A parallel tuned pickup has a reflected load that includes a capacitive element (independent of load) that effectively shortens the track during operation. This is usually undesirable due to the VAR loading presented on the track, unless the added capacitance is compensated for with track tuning. For AGV applications this capacitance has the advantage of cancelling out (in practice usually overcompensating) the added inductance due to the pickup ferrite. Given
that most modern IPT resonant supplies operate at a fixed frequency and use an LCL network at the output (the last L representing the track), smaller track inductances are preferred [120]. The LCL tuning acts as an impedance conversion network, with the resulting impedance given by:

\[ Z_{\text{in}} = \frac{X^2}{Z_{\text{Load}}} \]  
(4.6)

where the reactance, \( X \) of each tuning element is matched. The capacitive load presented by a parallel tuned pickup appears as an inductive load to the switches in the IPT supply, and can be driven provided that the switches are rated for the extra VARs. In contrast, a capacitive load on the inverter greatly increases the switching losses due to the reverse recovery currents of the switch body diode [119, 128]. As such, most switches cannot drive the capacitive load from a track inductance larger than nominal, and a slight overcompensation of the pickup reflected impedance is preferred for most modern IPT systems.

However, (4.5) does not take into account the effect of partial series compensation which further reduces the reactance of the pickup, with the effective reactance given by:

\[ X = \omega L_2 - \frac{1}{\omega C_{L2}} \]  
(4.7)

When this is applied to the LCL tuning topology in (4.5), the reflected impedance is increased, but still consists of only a real component, reflecting only resistance. For the parallel tuned pickup, the reactive component is also affected. Substituting (4.7) into the parallel tuned pickup equation in (4.5) enables the reflected impedance of a partially series compensated parallel tuned pickup to be described as:

\[ Z_r = \frac{\omega^2 M^2}{\omega L_2 - \frac{1}{\omega C_{L2}}^2} \left( R - j\omega L_2 + \frac{j}{\omega C_{L2}} \right) \]  
(4.8)

With the quadrature pickup, the reflected impedance is further complicated by the combined operations of the two coils with lateral movement. The above equations can be modified so that the change in track inductance can be modelled using the parameter \( S_U \). For simplicity, the parallel tuned pickup is initially considered without series tuning (The full derivation including partial series tuning is presented in Appendix A).
Only the reactive component of (4.5) is of interest, as this affects the track inductance that the power supply sees, so removing the real component gives:

\[ X_r = -j\omega M^2 X \]
\[ = -jM^2 \frac{L}{\omega} \]  
(4.9)

Where \( X = j\omega L_2 \), as series tuning is not included. The form is similar to the equation for uncompensated power of a pickup:

\[ S_U = \frac{M^2}{L_2} \cdot j\omega I_1^2 \]  
(4.10)

Combining (4.9) and (4.10) gives:

\[ X_r = -\frac{S_U}{I_1^2} \]  
(4.11)

In the case of the quadrature pickup, the reflected reactance of the two coils can be summed as the coils act independent of each other:

\[ X_r = -\frac{M_{2H}}{L_{2H}} j\omega \frac{M_{2V}}{L_{2V}} j\omega \]
\[ = -\frac{S_{U(Horizontal)}}{I_1^2} - \frac{S_{U(Vertical)}}{I_1^2} \]  
(4.12)

To give the change in track inductance, the operating frequency is considered:

\[ \Delta L = \frac{X_r}{\omega} = -\frac{S_{U(Horizontal)}}{\omega I_1^2} + \frac{S_{U(Vertical)}}{\omega I_1^2} \]  
(4.13)

In this form it is easy to consider any partial series compensation. The each coil is individually tuned, so applying the respective \( Q_i \)’s to (4.13) gives:

\[ \Delta L = -\frac{Q_{i(H)} \cdot S_{U(H)} + Q_{i(V)} \cdot S_{U(V)}}{\omega I_1^2} \]  
(4.14)

While it is possible to calculate the change in track inductance from measurable parameters, it is not possible to calculate the increased inductance due to the pickup ferrite. This must either be measured directly, or simulated in the design stage before a pickup is constructed.

The simulation model from the previous chapter was used, with the pickup coils simulated
open circuit. To find the reflected impedance, the voltage in the track was measured with the track current set to 125A operating at 20kHz. The resistance of the track was minimised so that the change in track impedance consists of only the reflected impedance. The track was also simulated without the pickup in place to give the track inductance, so that the results could be normalised. In all cases the track length was 1m. These results are compared to the measured results of Figure 4-6.

The change in track inductance when the quadrature pickup is introduced onto the track, and is operating with various tuning topologies was measured on a short 1.5m length of track while connected to an LCR meter set to measure at 20kHz (the track operating frequency). The length of track was kept large enough such that end effects are considered, but also kept as small as possible to keep the track inductance low so that changes are easily measured. The constructed pickup is the one from section 4.3 with the 39 turn horizontal coil, and pickup height was maintained at 20mm.

Figure 4-5 shows the increase in track inductance as the pickup ferrite is moved across the track (both coils open circuit). When the pickup is centred on the track the track inductance is 1.345µH, an increase of 28nH over the inductance without the ferrite in place (1.317µH). This increase reaches 32nH when the ferrite is over the track conductors (50 to 70mm offset). While this increase appears small, with multiple pickups operating the increase in inductance is significant.

![Figure 4-5: Inductance of the track as pickup ferrite is introduced.](image)

The change in track inductance due to the parallel tuning is measured using the same methodology as above. When both coils are both short circuited, the load impedance $Z_L = 0$
From (4.5) the impedance reflected onto the track is due only to the pickup tuning topology. This is shown when the inductance of the track is measured as the shorted quadrature pickup moves across as shown in Figure 4-6(a). Also shown are the effects of the individual coils and the ferrite alone. These results are for the pickup without any series compensation (shorted before the series tuning capacitor). To measure the results with series compensation, the coils were shorted after the series tuning capacitor, with the results shown in Figure 4-6(b). In both cases the inductance of the track without the pickup present has been subtracted to indicate the change in inductance from the designed value.

To validate the simulation and calculation techniques presented earlier, these are presented with the measured results of Figure 4-6. The simulated $S_U$ results for the quadrature pickup presented in Chapter 3 were applied to (4.14), along with the track current of 125A at 20kHz. A $Q_I$ of 2.25 for the horizontal winding was used to match the constructed pickup, with the results presented in Figure 4-6(b).

![Figure 4-6: Measured and simulated/calculated results of normalised track inductance with the quadrature pickup; (a) no series compensation, (b) partial series compensation.](image)

The results clearly show that parallel tuning reflects a capacitance back onto the track, and over-compensates for the added inductance due to the pickup ferrite also shown in Figure 4-6(a). The effect of the vertical coil is also more pronounced than that of the horizontal coil, due to the higher coupling of the vertical coil. When the pickup is centred on the track, the inductance is reduced by 72nH due to the tuning, resulting in a 40nH reduction seen by the power supply. At offsets greater than 60mm, the reduction in track inductance matches that introduced by the pickup ferrite, with a resulting change in track inductance practically zero.
The reflected impedance as seen by the track is further affected when series tuning is included on the pickup. The reduction is changed from 32nH in for the horizontal coil with no series compensation, to 79nH for the series compensated horizontal coil (Figure 4-6b). This change is proportional to the $Q_i$ applied (2.25 for the pickup measured). The resultant track inductance is reduced by 47nH below the designed inductance when the quadrature pickup with series compensation is located at 50mm. The result is a fairly consistent track inductance as the pickup moves across the track between ±80mm (Ideally a $Q_i =2$ should be used to improve the balance between the two coils).

Also shown in Figure 4-6 are the results from simulation and calculation for a pickup with and without series compensation using (4.14). These results match the measured results well, sufficient to be used to design pickups and tracks before the pickup is constructed. From (4.14) it can also be deduced that the reduction in track inductance is unaffected by the number of turns on the pickup, as $S_u$ (the only dependent variable) is unchanged by $N_2$ as explained in Chapter 3. Therefore, the quadrature pickup with a 19 turn horizontal coil described in Section 4.3 will experience a change in track inductance identical to that shown in Figure 4-6(a).

The change in track inductance when the flush quadrature pickup with a 40mm centre extension, as described in Chapter 3, is moved across the track can also be modelled using (4.14). A $Q_i =1.7$ was applied as in Section 4.2, and here the simulations show track inductance with and without series compensation in Figure 4-7(a) and (b) respectively.

![Figure 4-7: Simulated/calculated results of normalised track inductance with the 40mm extended quadrature pickup; (a) no series compensation, (b) partial series compensation.](image-url)
Due to the extra ferrite in the pickup and the change in track width, the increase in inductance as the pickup moves across the track (Figure 4-7a) is 53nH, larger than the previous results of 32nH. The reduction in track inductance is inductance 26nH below that designed when the pickup is centred on the track, however, for a large offset range (50mm to 150mm) the resultant inductance change seen by the power supply is practically zero. Series compensation changes this, balancing the effect of both coils (Figure 4-7b) resulting in a reduction of 20 to 30nH from the designed track inductance.

For AGV systems, it is clear that parallel tuning is desirable to compensate for the added track inductance when the pickup ferrite is moved across the track. This can easily be modelled for various designs before constructing the pickup or track. The decision to use partial series compensation is up to the system designer. Without the partial series tuning the compensation is sufficient to result in zero change in track inductance for most offsets, but with a reduced inductance when the pickup is centred. However, with appropriate series compensation the change in track inductance with the quadrature pickup is well balanced over a wide offset range.
4.5 Flux

One important consideration when designing pickups is to ensure that the flux density is within the limits of the ferrite. If the flux density went beyond these limits and the ferrite saturates, the losses in the pickup rapidly increase and thermal runaway will occur, damaging the pickup. Normally, other issues such as ferrite brittleness and coupling strength limit the maximum power of the pickup before the flux density becomes a problem, but as improved high power designs are considered, care must be taken to avoid saturation.

In the previous chapter the flux density in the pickup was considered when designing the ferrite structure. This restricted the depth of the window area for the horizontal coil in the flush quadrature pickup design. When a pickup is tuned, the flux in the pickup increases and is dependent on the tuning topology used. The relationship between the tuning and the flux is given by [91]:

\[
\Phi_2 = \begin{cases} 
\frac{MI_1}{N_2} (1 - j \frac{\omega L_2}{X^2}) & \text{parallel tuned} \\
\frac{MI_1}{N_2} (1 - j \frac{\omega L_2 R}{X^2}) & \text{series tuned} \\
\frac{MI_1}{N_2} (1 - j \frac{\omega L_2 R}{X^2}) & \text{LCL tuned}
\end{cases}
\]

(4.15) can be written in term of \(Q, Q_t\), and \(Q_r\), noting that for series tuned \(Q = \omega L_2 R\):

\[
\Phi_2 = \begin{cases} 
\frac{MI_1}{N_2} (1 - Q_t - jQ) & \text{parallel tuned} \\
\frac{MI_1}{N_2} (1 - jQ) & \text{series tuned} \\
\frac{MI_1}{N_2} (1 - jQ) & \text{LCL tuned}
\end{cases}
\]

(4.16)

In order to confirm that the previous equations accurately describe the flux in the pickup with various tuning topologies, a set of simulations were carried out with a simple flat bar pickup. The pickup consists of a ferrite bar of dimensions 60mm \(\times\) 10mm \(\times\) 30mm and a 20 turn coil covering 60% of the ferrite. This was simulated at a height of 10mm while centred above the track, which was a single conductor with 20A current at 38.4kHz. The pickup is tuned, and a resistive load is applied to simulate for various \(Q_r\)'s, while the series tuning capacitor is varied for \(Q_t\). The results are presented in Figure 4-8.
When the parallel tuning topology is used without any series tuning ($Q_s = 1$), the flux increases linearly with $\kappa_p$. However, as $Q_i$ is increased, this no longer holds true, as shown in Figure 4-8 and (4.16). The flux increases with $Q_i$, even though the total $Q$ of the pickup is maintained. Because of this, $Q_i$'s above 2 to 3 are not recommended, without carefully investigating to ensure the resulting flux density is within the limitations of the pickup ferrite, especially if areas of high flux density (such as those presented in Chapter 3) exist in the ferrite.

When the LCL tuning topology is used, the flux in the pickup is unchanged with various $Q_i$'s, provided the total $Q$ remains constant. The flux in the pickup is equivalent to the parallel tuning topology operating with a $Q_s = 2$. While the flux in the pickup does not change, the flux in the second inductor ($L_2$) increases due to the increased current, and must be
appropriately rated. While the LCL tuning topology is an option for control [91], this thesis focuses on parallel LC tuning given the $Z_r$ characteristics.

The majority of pickups must tolerate some movement above the track, and in the case of AGV systems, this can be substantial unless tight controls are used with appropriate sensors. With movement, the $V_{OC}$ of the pickup changes, along with $Q_v$ to achieve the desired output voltage. The quadrature pickup presents further challenges as it uses two coils coupled to the track, which both resonate to full voltage over the majority of the designed offset range, even when the coil is not delivering power, as discussed in Section 4.3. Because of this and without any control, at some offsets the coils will operate with large $Q_v$'s, higher than is typical with standard pickups.

To investigate how the flux in the pickup changes as the pickup moves across the track, the operating $Q_v$ must be calculated. When the pickup is operated with a $V_{DC} = 300V$, the resonant voltage of each coil is 333V. Assuming that the coils can resonate to full voltage at any offset, the $Q_v$ can be calculated using the $V_{OC}$ results from Chapter 3, shown in Figure 4-9(a). The resulting $Q_v$ profile is shown in Figure 4-9(b), which can then be used to calculate the flux in the pickup. Substituting $V_{OC} = j\omega MI_1$ into (4.16) gives:

$$\Phi_2 = \frac{V_{OC}}{j\omega N_2} \left(1 - Q_v - jQ\right)$$  \(4.17\)

The results of (4.17) are shown in Figure 4-9(c), and compared against simulated results. For the simulation, the pickup was tuned using the values in Table 4-1, with a resistive load applied. The value of the load was adjusted for the pickup to operate at the resonant voltage of 333V.

As the pickup moves across the track, the flux in the pickup is almost constant, shown by the calculated results in Figure 4-9(c). This assumes that the coil resonates to full voltage, without coil losses to restrict the operating $Q_v$. In reality, the resonant circuits are not lossless, and the $Q_v$ will be limited. The simulated results in Figure 4-9(c) include minor winding loss in the pickup coils, which gives a mismatch between the calculated and simulated results, but for $Q_v < 10$ the practical and simulated results are well matched, as noted in Figure 4-9(b) and (c). In practical materials handling applications when the pickup movement is constrained the $Q_v$ is normally limited by design to values below 10, but such
limitation is not possible here unless some movement restriction is imposed. In materials handling applications the actual flux will be below the value calculated with (4.17), and can safely be used when designing the pickup. From Figure 4-9(b) it can be noted that the $Q_y$ of the horizontal coil is high when the vertical coil $Q_y$ is at a minimum and vice versa. If each coil is independently switched such that the pickup delivering negligible power (and operating with a large $Q_y$) is decoupled, the flux in the pickup can be reduced.

![Figure 4-9](image)

**Figure 4-9**: Simulated and calculated results of the quadrature pickup; (a) $V_{OC}$, (b) Operating $Q_y$, (c) Operating pickup flux in each coil.

Notably if two pickups with different turns on the horizontal coil are designed to give identical partially compensated outputs ($Q_l \cdot S_U$), such as could be the case with the quadrature pickup operating with a 19 turn horizontal coil with a $Q_l = 1$, and with a 39 turn horizontal coil
with a \( Q_t = 2 \), the flux in the pickup from either horizontal coil is similar. This is expected from (4.17). The 19 turn coil has half the number of turns (of the 39 turn coil) and \( V_{oc} \) is also half. The flux is slightly lower for the 39 turn horizontal coil, but the difference is negligible. When designing the quadrature pickup, there is no significant difference in the operating flux with either coil when operating with identical \( Q_t \cdot S_u \), so the choice between the coils is based on other factors. Despite the difference between calculated and simulated results due to resonant losses, (4.17) can safely be used to calculate the flux in a pickup.
4.6 Efficiency

As noted earlier in the chapter, both of the coils on the quadrature pickup experience their full resonant current independent of the pickup position (unless precisely aligned with their respective power nulls). When one of the coils is barely delivering power, the other coil is delivering almost full power, with the DC bus at full rated voltage. As such, the coil with the lower coupling only needs to overcome the losses in the resonant tank circuit for that coil to resonate up. With full resonant current circulating in both coils and the associated losses in each resonant tank, the total pickup losses are larger than those found in traditional vertical pickups, and as a result, the quadrature pickup is less efficient without some additional control.

To evaluate the efficiency of the quadrature pickup measurements were taken with only the vertical coil in operation, and with both coils operating. The controller circuit first presented in Chapter Three and used throughout this chapter was used to regulate the output at 300V DC into a 400W load. Under conditions where the 300V output could not be maintained, the output load was reduced to allow 300V output (or the highest voltage possible), such that the pickup was operating at the maximum power point (where no controller regulation occurs). To measure the efficiency of the pickup, the mains AC input power into the IPT supply and the DC output power of the pickup are measured using the AV Power PA4000 power analyser. The power loss of the IPT supply and track were measured without the pickup in place, and subtracted from the input power. This was possible as the power supply used regulated the track current, and was allowed to reach a constant operating temperature before measurements were taken.

This method of measuring efficiency was chosen as all the losses in the pickup, including the losses in the pickup magnetics needed to be considered. An alternative method involved measuring power delivered from the track. This real power is small in comparison to the VAR’s in the track and required precise phase measurements between the voltage and current of the track. This method was impractical due to the frequency and magnitude of the track current and the limitations of the measuring equipment available.

The results of the measurements are shown in Figure 4-10, with the output DC power and efficiency respectively shown for the 39 turn horizontal coil (Figure 4-10a, b) and the 19 turn horizontal coil (Figure 4-10c, d). The output power measurements of both pickups are very similar; when only the vertical coil is in operation the pickup is in regulation for a small offset range (±10mm). When both coils are operating (quadrature operation) the pickup regulates over an offset range of ±110mm.
When both pickups are operating with the quadrature coils, the efficiency of both pickups is similar with an average of 91–92%. In the case of both pickups, when only the vertical coil is operating, the efficiency is 94–95% over the range of regulation in the centre of the track (±10mm). This 3% difference in efficiency is significant and can be avoided.

![Graphs showing output power and efficiency](image)

**Figure 4-10**: Output power (400W regulated) and Quadrature pickup efficiency respectively with various coils operating: (a, b) 39 turn horizontal coil; (c, d) 19 turn horizontal coil.

When the pickup is centred on the track, the vertical coil provides sufficient power to the pickup, and operating the horizontal coil simply reduces the efficiency of the pickup because it is allowed to resonate. Likewise, when the pickup is located above a track conductor, the horizontal coil supplies sufficient power and the vertical coil simply adds losses. A simple solution is to decouple the coil not supplying power in order to minimise the resonant losses thereby increasing the efficiency. To determine when the coils should be decoupled, the current that each coil contributes needs to be measured since this is a direct measure of the available power in a parallel tuned system. The circuit must also be modified to allow
individual switching of the two coils, by adding an additional DC inductor, switch and diode. A possible circuit with current feedback is shown in Figure 4-11.

![Figure 4-11: Quadrature pickup circuit and feedback for individual coil operation.](image)

The available current of each coil can be measured during operation and compared against a predetermined threshold based on the rated power of the pickup and the output voltage, along with the magnitude of the current feedback from the other coil (Figure 4-12). For the prototype, an output voltage of 300V for a rated power of 400W gives a threshold of 1.33A, which is indicated in Figure 4-12(a) and (b). When the current of one of the coils (i.e. the vertical coil) is above this threshold, the switch for the other coil (i.e. the horizontal coil) is turned on, decoupling that coil and minimising the losses. When not decoupled, the switch operates as normal under PWM or hysteresis control. A minimum threshold level for each coil could also be specified to prevent the coils resonating when the coupling to both coils is not sufficient to power the load.

In addition to this, extra conditions are applied to further improve the efficiency by reducing switching losses. If neither coil is above the threshold, the coil with the higher current is not switched at all to provide full power, eliminating switching losses for that switch, while the other coil is under PWM or hysteresis control to regulate the output of the pickup. The resulting switching patterns for the individual coil decoupling switches are shown in Figure 4-12(c) and (d) for the 39 turn and 19 turn horizontal coil quadrature pickups respectively.

The individual switching of each coil does improve the efficiency of the quadrature pickup when centred on the track for both the 39 turn and 19 turn horizontal coil pickups (Figure 4-13). The results of the quadrature pickup with the 39 turn horizontal coil (Figure 4-13a) show small improvements in efficiency over the full offset range, with an average of 93%.
The significant improvement is between the ranges of ±10mm, where the horizontal coil is decoupled, and closely matches the efficiency profile of only the vertical coil operating, reaching 95% efficient when centred on the track.

Improvements using this technique with the quadrature pickup with the 19 turn horizontal coil are less clear (Figure 4-13b). When the pickup is centred over the track (offset range of ±10mm) and the horizontal coil is decoupled, the efficiency profile is similar to when only the vertical coil is operating. However, the efficiency at offsets beyond this range are below that of both quadrature coils operating simultaneously, specifically between offsets of -70mm to -20mm and 20mm to 40mm. This corresponds with the offsets in the switching patterns of Figure 4-12(d) where one coil is not switched (supplying full power) and the other is switching to regulate the output. A solution to this is a simplified control where only the current threshold level is considered, such that if the current of either coil is not above the threshold, both coils are regulated with PWM control. A variation on this is considered later in this section where a simple AC switch is employed.

![Graphs showing feedback currents and decoupling switch patterns](image)

**Figure 4-12:** Feedback currents ($Q_i \cdot I_{sc}$) and the resulting decoupling switch patterns: (a, c) 39 turn horizontal coil; (b, d) 19 turn horizontal coil.
The above results do not allow for a fair comparison between the quadrature pickups with and without series tuning, due to the differing $Q_i \cdot I_{SC}$ profiles between them. This is particularly evident with the switched efficiency profile, due to the variation in switching duty cycles. This is a result of applying a $Q_i$ of 2.25 to the 39 turn coil, whereas the 19 turn coil only exhibited an $I_{SC}$ twice as large. For a fair comparison, a quadrature pickup with a 16 turn horizontal coil was wound where the $I_{SC}$ matches the $Q_i \cdot I_{SC}$ of the 39 turn horizontal coil quadrature pickup. The efficiency of these two pickups operating with the switching pattern of Figure 4-12(c) are shown below in Figure 4-13.

Both the 16 turn and the 39 turn horizontal coil quadrature pickups are similar in efficiency, averaging 93% over the full offset range, and operating at 95% efficiency when centred on the track. Based on only the efficiency, neither quadrature pickup has a disadvantage over
the other, and any choice between designs should be based on other factors such as core
flux, winding space and reflected impedance.

One of the issues of switching the quadrature coils individually to improve efficiency when
centred on the track is the introduction of extra components. Three of these components; the
DC inductor, switch and diode add significant cost to the pickup due to the power rating
required. Considering that the biggest improvement in efficiency arises when the pickup is
centred on the track (for the single phase bipolar track considered), another approach is to
only decouple the horizontal coil when the vertical coil is contributing fully to the output.

A simple AC switch can be used to decouple the coil on the other side of the rectifier (Figure
4-15), so that the only introduced power component is the AC switch. Earlier a simplified
switching scheme was discussed based only of a threshold current value. This can be
applied to the AC Switch, and only requires feedback from the vertical coil, saving further
components.

Due to the very low switching frequency, options for this AC switch include MOSFETS, or a
relay synchronised to the operation of the main switch S. The relay would then be switched
when both coils are decoupled. Note that it may be desirable to include a similar AC switch
for the vertical coil when the quadrature pickup is operated on meander tracks presented in
Chapter Five. Including the AC switch for both coils is a significant reduction in cost and
complexity compared with the individual switching option first presented.

Figure 4-15: Quadrature pickup circuit and feedback for decoupling the horizontal coil with an
AC switch (Optional Horizontal feedback indicated with dashed line)
4.7 Guidance

Because the quadrature pickup has two individual coils the outputs of each could be used to provide steering signals to an AGV to centre the pickup on the track, thereby eliminating the need for additional sensors. The feedback required for this can be either the voltage or the current of each coil. One method is to consider the phase, but requires AC feedback from the coils. Figure 4-16(a) shows the feedback at one instance in time, when the current in the track is at the peak. The advantage of these signals is that the polarity of the horizontal coil indicates which side of the track the pickup is on, but the polarity changes based on instantaneous track current.

The polarity of the vertical coil is an indirect measure of the phase of the track. By using the polarity of the vertical coil as a reference for the horizontal current feedback, the resulting signal as shown in Figure 4-16(b) can be used to determine which side of the track the pickup is located. The magnitude of this signal will still vary with the track current, but the polarity of the resultant feedback is constant at any given offset. The phase detection simply determines whether the feedback of the horizontal is positive or negative to give steering signals, and searches for the zero crossing to locate the centre of the track. However, the extra zero crossings at ±75mm limits the effective range of this location feedback.

A second option to locate the centre of the track is to determine the maximum point of the vertical coil. Both options would be restricted to single phase systems, as both the phase and magnitude of the coils do not necessarily correspond with the centre of the track in poly-phase systems. Location detection has not been implemented on the quadrature pickup, as it

Figure 4-16: AC current feedback from each coil (a) and the resultant feedback comparing the horizontal feedback polarity to the vertical feedback polarity (b).

A second option to locate the centre of the track is to determine the maximum point of the vertical coil. Both options would be restricted to single phase systems, as both the phase and magnitude of the coils do not necessarily correspond with the centre of the track in poly-phase systems. Location detection has not been implemented on the quadrature pickup, as it
was beyond the scope of this thesis. However, it is an interesting feature of the quadrature pickup that should be developed further.

4.8 Conclusions

The contributions from each of the coils on the quadrature pickup cannot easily be equalised by magnetic design alone, electrical compensation is also required. To balance the power from each coil two tuning methods are presented, standard parallel tuning, and adding partial series compensation. This chapter investigated the impact of these tuning methods on the flux in the pickup ferrite, the pickup operating efficiency, and the reflected impedance seen by the IPT supply.

When the compensation was kept within reasonable values, there was no significant benefit in choosing between the parallel tuning topology with and without partial series compensation. The final decision to use partial series compensation was based on the desired reflected impedance seen by the power supply, which may differ between applications. For the single phase track investigated in this chapter, partial series compensation operating with a $Q_f$ of 2 was preferred, as this reflects a constant impedance on the track. The efficiency of the pickup was also investigated for both tuning methods, and an improved controller capable of individually switching the coils was presented. This enabled the quadrature pickup to operate with similar efficiency to a standard vertical pickup, while delivering power over a much greater range.
5 Multiphase and Repeated Single Phase Tracks

5.1 Introduction

The previous two chapters have investigated a new magnetic pickup structure to increase the lateral range of power delivery for IPT systems. This has been achieved by capturing both the tangential and normal components of magnetic flux around the track conductors. This design has been investigated on single phase track configurations with the goal of retrofitting the pickup to existing IPT system installations, or further improving the lateral range with minor track modification.

An alternative means of increasing the lateral range over which power is effectively delivered in IPT systems is with further modification to the track layout. Such modifications include the use of repeated single phase (or meander) track arrangements and the use of poly-phase track configurations. The quadrature pickup can also be used with these modified tracks to further extend the lateral range of power delivery, or to deliver greater power to the pickup, and overcome some of the limitations of these track arrangements.

This chapter investigates the use of the quadrature pickup on both meander and poly-phase track configurations through simulation and measurement with a small scale pickup. The full scale pickup is then modelled on these tracks using magnetic superposition. This allows various multiphase track configurations and uneven track spacing to be modelled quickly using a set of simulations of the pickup over a single track conductor.

5.2 Repeated Single Phase Tracks

The first modification to the track for increasing the range of lateral movement of an IPT pickup is using a repeated single phase or meander track layout. The track conductors are arrayed across the desired overall track width (x direction) with 180° phase difference between neighbouring conductors (i.e. phase and return). This modification is easy to implement, using either individual synchronised power supplies driving the individual repeated tracks as shown in Figure 5-1(a), or using a meander track layout driven by a single power supply (Figure 5-1b), further simplifying the design.
Because the meander track configuration is based on a single phase bipolar track layout, the same issue exists when using traditional flat pickups; the presence of null points in the power profile with lateral offset. As discussed in Chapter 3, these pickups capture only one directional component of the magnetic field. Due to the 180° phasing between the track conductors, points exist where the magnetic flux component reduces to zero. In previous work, multiple pickups at different offsets have been used to overcome this limitation [16]. As described in Chapter 3, the quadrature pickup captures both the horizontal and vertical components of the magnetic field which results in a power profile without nulls compared with the power profile exhibited with standard flat pickups. Because of this, the quadrature pickup is ideal for use on meander track configurations.

The quadrature pickup was tested on a meander track consisting of six track conductors, simulated with 40A per conductor and spaced 80mm apart. The low power prototype initially simulated on the meander track is described in Section 3.3 and 3.4, with 100% fill area and 50mm in length. This particular track current and pickup prototype was chosen for the work in this chapter to enable direct comparison with earlier results using a Quadrature receiver. The results from the simulation are shown in Figure 5-3.

The results show the effectiveness of the quadrature pickup to couple across a wide power zone, increased by the meander track configuration. In this case, the offset range is increased from ±70mm (Figure 3-9) to greater than ±220mm (Figure 5-3c). There are clearly no null points in the power profile of the quadrature pickup. However, the $S_U$ does vary greatly for different lateral offsets, as the pickup is too wide for the track spacing. In the centre of the track, the pickup is coupled to multiple track conductors, and the magnetic flux from these conductors opposes each other in the pickup ferrite. This flux cancellation reduces the power transfer and overall coupling in the track centre, shown in Figure 5-3(a).
Near the edge of the track the pickup is coupled to fewer track conductors, and less flux cancellation occurs, allowing greater power transfer at offsets between 170 – 220mm.

Figure 5-3: $V_{oc}$, $I_{sc}$ and $S_U$ results of the quadrature pickup on a six conductor meander track with 80mm conductor spacing.

To reduce the amount of flux cancellation that occurs, the track spacing needs to be optimised for the pickup design. Various conductor spacing, from 80mm – 140mm were simulated to find the one appropriate for the quadrature pickup ferrite, with the results shown in Figure 5-4 and Figure 5-5.
Figure 5-4: $V_{oc}$, $I_{sc}$ and $S_u$ results of the quadrature pickup on a six conductor meander track with a conductor spacing of; (a-c) 120mm, (d-f) 140mm.
As the track spacing is increased from 80mm to 120mm, the pickup is primarily coupled to only one (horizontal coil) or two (vertical coil) track conductors shown in Figure 5-4. As a result, the opposition of flux in the pickup from each conductor is minimised, and the resultant $S_U$ profile is greatly improved. The variation in $S_U$ is reduced to ±1.5VA (6 – 9VA), which is an improvement compared with the pickup $S_U$ when operating above tracks with 80mm and 100mm track spacing which have ±3VA and ±2.5VA over ranges 2 – 8VA and 5 – 9VA respectively. The offset range over which this power can be delivered also increases to ±340mm with the 120mm track spacing, while still ensuring a minimum output of 6VA. When the track spacing is increased further to 140mm, the coupling of the pickup is reduced, and the variation in $S_U$ increases to 5.5 – 9.5VA. While an $S_U$ of 5.5 can be maintained over a larger offset range of ±400mm with this track spacing, the large variation in $S_U$ is undesirable.

![Figure 5-5: The quadrature pickup on a six conductor meander track with various conductor spacing.](image)

From these results (shown comparatively in Figure 5-5), the optimal track spacing for this quadrature pickup design is 120mm. This differs from the industry standard 100mm track spacing used with the commercial F-pickup from which this quadrature pickup is derived. However, this is because the F-pickup only captures the vertical flux component. With a track...
spacing less than the optimal 120mm (Figure 5-4a), it is primarily the flux captured by the horizontal coil which is in opposition, with a smaller effect on the vertical coil flux as shown in Figure 5-3(a). As the track spacing is further increased beyond the optimal 120mm, less opposition of flux occurs in the horizontal coil as the influence of the other track conductors becomes negligible, until it reaches an asymptotic peak of approximately 10V for this design. This trend is clearly shown in Figure 5-6(a), which plots the peaks in the output of the pickup near the centre of the track. The vertical coil is at an optimum with 100mm track spacing (Figure 5-6a), corresponding with the industry standard for commercial F-pickups this pickup is based upon. This is due to the track conductors aligning with the windings of the vertical coil, as discussed in Section 3.8. However, for the quadrature pickup, it is the combination of the coils which determine the optimal track width. Ideally, the values for the horizontal and vertical coils should match to minimise variation in output, which is true of the 120mm track spacing with this pickup design shown in Figure 5-6.

![Graphs showing peak outputs](image)

Figure 5-6: The peak outputs; (a) $V_{oc}$, (b) $I_{sc}$, (c) $S_U$ from the quadrature pickup operating near the centre of a meander track with various track spaces.

The meander track configuration is clearly a viable means of increasing the allowable lateral movement of a quadrature IPT pickup, and is easily applied in practice using a single IPT
supply. It is necessary to optimize the track conductor separation together with the magnetic pickup structure to ensure a smooth power delivery across the offset range desired. This range can be further improved by adding more track conductors, although track losses and cost will place practical limits on such systems.

5.3 Poly-phase Tracks

Poly-phase track configurations have recently been introduced as an alternative means of increasing the offset range over which pickups can deliver power [16, 24, 68]. These consist of multiple track conductors with currents of varying phase. Typically these conductors are evenly spaced apart, and the phase of the current between neighbouring conductors is equal and sequentially ordered as shown in Figure 5-7 and Figure 5-8. This is similar to the windings of an induction motor that have been laid flat, and like an induction motor, this generates a rotating magnetic field around the track. Due to the flat nature of the track, this appears as a travelling magnetic wave in the near field where pickups typically operate. To date, pickups used on poly-phase tracks have only captured the horizontal flux component, this section investigates the benefits of capturing both components on these tracks.

![Figure 5-7: Three phase bipolar track configuration.](image)

![Figure 5-8: Three phase track conductors and current phasor diagram.](image)

The quadrature pickup was tested on a three phase bipolar track consisting of six track conductors each with 40A, separated in phase by 60° and spaced 40mm apart [24, 68]. The pickup used was the low power prototype of the quadrature pickup described in Section 3.3, with 15 turns per coil using light hook-up wire. Note that the windings do not fill up the
window area completely. This was deliberately done to enable direct comparison of the simulated results with those measured on a three phase bipolar track available in the lab [24]. As shown in Figure 5-9, both measured and simulated results show good agreement. Later in the section the quadrature pickup is simulated with 100% coil fill factor to maximise coupling of the pickup.

The $S_U$ of the individual windings and the combined quadrature profile are shown in Figure 5-9. The horizontal winding (similar to a flat bar pickup) has a peak $S_U$ of 16VA, and maintains 12VA over an offset range of ±110mm, equivalent to the distance between the two outer track conductors. The quadrature pickup does not increase the range that power can be delivered for a given track spacing, but the power delivered is increased due to the addition of the vertical windings output. With 40mm conductor spacing, 15VA can be maintained over ±100mm, or a higher $S_U$ of 22VA can be maintained over an offset range of ±60mm.

![Figure 5-9: Measured and simulated $S_U$ results for the quadrature pickup on a three phase bipolar track with 40mm conductor spacing.](image)

The real advantage of the quadrature pickup is that greater track spacing can be used to increase the offset range that power is delivered over, while maintaining an $S_U$ matching that of a flat bar pickup (horizontal winding) on a track with smaller spacing as shown in Figure 5-9.
Here the same pickup as previously simulated is used, but with 100% coil fill factor to maximise the coupling of the pickup as described in Chapter 3.

Again considering the track with 40mm conductor spacing, the horizontal coil now maintains an $S_U$ of 18VA over a range ±100mm (against an $S_U$ =12VA without 100% coil fill factor).

With the quadrature coil arrangement, the $S_U$ reaches 42VA with the pickup centred on the track. For an identical offset range (±100mm), the $S_U$ of the quadrature pickup is 23VA, an improvement over the horizontal winding. However, when the conductor spacing is increased to 80mm, the $S_U$ can be maintained at 18VA over a range of ±180mm, matching the $S_U$ of the horizontal winding on the 40mm spaced track with an 80% increased lateral tolerance. With a further increase in conductor spacing, the lateral range over which power can be delivered is increased, but the $S_U$ is reduced.

Figure 5-10: Simulated $S_U$ results for the quadrature pickup on three phase bipolar tracks of various conductor spacing.

Depending on the application requirements of the IPT system, the three phase system can be adjusted for either an increase in power, or an increase in lateral tolerance. This is possible as the quadrature pickup maintains a consistent $S_U$ profile over the range, whereas pickups capturing only the horizontal or vertical flux component are subject to large variations.
in output. These initial simulations of the quadrature pickup on both three phase and meander track configurations show that the three phase track layout offers advantages in pickup output and flexibility in setting the track width for a desired lateral pickup tolerance. However, this does not account for the entire IPT system and the impacts that various track layouts have on the power supply. These impacts are presented in the following chapter, where IPT tracks with an equal number of track conductors are compared.

For a fair comparison, these and further track layouts are modelled at a scale suitable for industrial use, presented in Section 5.5.

### 5.4 Magnetic Superposition

As shown, the quadrature pickup can be advantageously used on a multitude of track configurations: So far, single phase, meander and poly phase tracks have been introduced, but these systems include many variables that can be modified. The number of track conductors, the spacing between these and the phasing and currents in each conductor can be altered to give different $S_U$ profiles. Attempting to simulate all of these combinations would take an impossibly large amount of time especially when combined with the number of variations of the quadrature pickup. However, analytical techniques such as superposition can be used to reduce the number of simulations required to model the quadrature pickup on these track configurations [24].

Using superposition, an arbitrary $N$-cable track arrangement with varying phase can be modelled using vector summation of the $V_{OC}$ and $I_{SC}$ responses of the pickup over the individual track conductors. This is true for non-saturating magnetic circuits, as these are inherently linear and can be modelled as a linear electronic circuit. The pickup can be simulated over a single track conductor (with any variation in $I_1$ or $\omega$ between conductors scaled using $V_{OC} = j\omega M I_1$ and $I_{SC} = V_{OC} / j\omega L_2$), assuming that no magnetic material is included in the track, as this creates further magnetic paths that need to be simulated separately.

This technique is described mathematically as follows, with the summation of the individual conductors ($V_{OCn}$) located at $x_n$ and with a relative track current phase of $\theta_n$:

$$V_{OC}(x) = \sum_{n=1}^{N} [V_{OCn}(x-x_n)\angle \theta_n]$$  \hspace{1cm} (5.1)

An identical approach is taken with the short circuit current, resulting in:
This technique is used throughout the remainder of the chapter to investigate further the effect of track spacing on the full scale pickup, firstly on tracks with even spacing, and then on unevenly spaced tracks recently proposed. It has been verified as accurate for flat pickups capturing the horizontal field component in previous research [24], and later in Section 5.5.1 is confirmed to be accurate for the quadrature pickup when compared to a simulation modelling the pickup operating on the full track.

5.5 Unevenly Spaced Tracks with an Industrial Scale Pickup

The simulations presented earlier in the chapter show that the quadrature pickup can be used on multiphase track configurations, however, the scale of the pickups modelled are not representative of those used in industry. As such, the flush quadrature pickup based on commercial F-Pickup designs, as presented earlier in Section 3.6 is used for the remainder of the simulations. As previously mentioned, the superposition technique is used to quickly model the various track configurations in this section. The first step to applying this technique is to model the pickup over a single track conductor in order to obtain \( V_{Oc_n} \) and \( I_{Sc_n} \), which can then be substituted into (5.1) and (5.2).

The conditions for these pickup simulations are given in Table 5-1 The impact of increasing z offset (height) relative to the track were simulated (as shown in Figure 5-11) to allow a variety of configurations to be modelled using superposition, but the resulting models focus on pickups operating at a nominal height of 20mm above the track. These results are used with (5.1) and (5.2) above, and by adjusting the individual track conductor locations, \( x_n \) and the phase \( \theta_n \), the flush quadrature pickup is modelled on three phase and meander tracks with equal and unequal conductor spacing.

<table>
<thead>
<tr>
<th>Table 5-1: Simulation Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary</strong></td>
</tr>
<tr>
<td>Track Current</td>
</tr>
<tr>
<td>(See Figure 3-8)</td>
</tr>
<tr>
<td>Operating Frequency</td>
</tr>
<tr>
<td>Track Spacing</td>
</tr>
<tr>
<td>Track Diameter</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Figure 5-11: $V_{OC}$ (a, b) and $I_{SC}$ (c, d) of the quadrature pickup horizontal and vertical coils respectively, operating over a single track conductor at various heights.

To confirm the superposition technique is accurate, it was used to model the full scale pickup on a three phase bipolar track, and the results compared against simulated results with all six conductors modelled. These comparative results are shown in Figure 5-14(a-c). As shown, there is a strong correlation between the simulated results and those calculated using superposition. Therefore this technique can be used to quickly assess different track configurations for viability.

### 5.5.1 Three Phase Bipolar Track with Even Conductor Spacing

As shown earlier in the chapter, the quadrature pickup outputs more power on the three phase track compared to traditional flat pickups, by capturing both magnetic field components. The combined output power profile has less variation which is a significant advantage. The lateral range of the pickup can be increased by spacing the track conductors
further apart but with a resulting decrease in power. The full scale pickup from Section 3.6 is
modelled on three phase bipolar tracks with 40mm and 80mm conductor spacing.

The pickup has a similar profile to the results of Figure 5-10, but the $S_U$ shown in Figure
5-14 is more realistic of an industrial scale pickup, reaching 1kVA when centred on the track
between ±40mm as shown in Figure 5-14(c). While suitable for applications that require high
power transfer, the lateral range of the pickup is fairly limited. A more practical scenario is a
track with 80mm conductor spacing. On this track, the pickup can deliver 500VA with a range
of ±180mm, as shown in Figure 5-14(f).

Regardless of the track spacing, both the $V_{oc}$ in Figure 5-14(a, d) and $I_{sc}$ in Figure 5-14(b, e) are fairly constant over the specified range of power delivery. This is the key advantage
that poly-phase tracks have over the repeated single phase tracks. Because of this, the
conductor spacing can freely be adjusted to give the desired lateral range or power.

### 5.5.2 Poly-Phase Tracks with Unequal Conductor Spacing

One of the considerations when designing a multiphase track is the mutual coupling between
track conductors. As the currents in the conductors are out of phase, the mutual coupling
causes unbalanced loading on the inverter, and may cause VA limits of the inverter to be
reached causing reduced power, or potential failure [24, 129]. In previous research this was
addressed in a variety of ways; using cable rotation, cable positioning and flux compensation
using mutually coupled toroidal ferrites [24, 129]. This research deemed cable positioning as
an unsuitable solution due the resulting uneven power profile produced by the flat pickups
that only capture the horizontal flux component modelled on the track. However, as the
quadrature pickup captures both the horizontal and vertical flux components, the resulting
output has less variation than flat pickup designs (Figure 5-15), and is therefore a better
option for this track layout.

To minimise the inter-phase coupling, the conductors must be spaced such that the track
loops of each phase overlap by 29% [24, 129]. For a three phase bipolar system, the outer
loops overlap the centre loop by 0.29, resulting in a change in phase order compared to the
previous evenly spaced three phase track as shown in Figure 5-13. However, the inter-phase
coupling between the outer phases cannot be completely removed, but is low due to the
distance between these phases. Furthermore, the exact track conductor spacing specified in
Figure 5-13 cannot be practically realised, and for this model is rounded to the nearest 10mm
due to the simulation increments (conductors located at -140mm, -60mm, -20mm, 20mm,
60mm, and 140mm). This three phase bipolar track was evaluated in Figure 5-15(a-c). In
addition, a two phase bipolar track was also modelled for comparison, shown in Figure 5-15(d-f) as a lower cost multi-phase system where the mutual coupling can be completely compensated for with ideal cable positioning.

![Figure 5-12: Three phase bipolar track configuration with 0.29 overlap.](image)

The output of the quadrature pickup is a significant improvement compared with that achieved from a flat pickup with only a horizontal winding, as shown in Figure 5-15. As with the single phase meander track results of Figure 5-4, the maxima in the horizontal outputs correspond with minima in the vertical outputs, and vice versa. By coupling both magnetic components, the output is higher than the output of a single coil pickup, and is generally flat near the centre of the track. The benefit of the quadrature pickup on this track layout is clear in the $I_{sc}$ output in Figure 5-15(b) and (e), with both the three phase and two phase bipolar tracks delivering 2.5A over ±100mm and ±60mm respectively.

However, when compared to the results of the same pickup on the evenly spaced three phase tracks in Figure 5-14, the uneven conductor spacing clearly has a detrimental effect on the output of the pickup. Higher outputs (Figure 5-14(a-c)), or a greater offset (Figure 5-14(d-f)) can be achieved with standard conductor spacing. As such, evenly spaced multi-phase tracks (utilizing flux compensation to minimise inter-phase coupling) are preferable to unevenly spaced tracks.
Figure 5-14: $V_{OC}$, $I_{SC}$ and $S_U$ results for the full scale pickup on a three phase bipolar track with 120mm (a-c) and 240mm (d-f) track spacing and 0.66 overlap.
Figure 5-15: $V_{OC}$, $I_{SC}$ and $S_U$ results for the full scale pickup on a 120mm spaced track with 0.29 overlap on; (a-c) a three phase bipolar track, and (d-f) a two phase bipolar track.
5.5.3 Repeated Single Phase Track

Repeated single phase or meander track arrangements offer a simple method of extending the range of power delivery to a pickup, with inverters powering the individual tracks operating synchronised in phase. In contrast, the three phase track presented earlier requires the inverters to operate 120 degrees out of phase, and a more complicated interface to synchronise the inverters is necessary [24, 128]. Additionally, a single inverter can be used to drive a track with a meander arrangement, with the same power profile as the repeated single phase (but with a reduced track length). This layout is modelled with the industrial scale pickup and conditions given in Table 5-1, at the standard conductor spacing of 100mm and the optimal spacing of 120mm, as shown in Figure 5-18.

With 100mm conductor spacing, the pickup can deliver 100VA over a range of ±300mm; however the output varies from 100VA to 300VA as shown in Figure 5-18(c). When operating on a track with 120mm conductor spacing, there is less variation in the pickup output, from 150VA – 250VA, delivered over a range of ±350mm shown in Figure 5-18(f). The optimal conductor spacing for single phase systems is 120mm with the specified pickup, limiting the structure of the track. While the output of the pickup on both tracks is lower than when operating on a three phase track, the lateral range which power is delivered is much greater. In theory, this lateral tolerance can be further increased by repeating the track conductors as often as required to achieve the necessary range.

The variation in output of the quadrature pickup when used on the meander track is due to the reduced output of the horizontal coil compared to the vertical coil. This is most evident in the $I_{sc}$ of the coils shown in Figure 5-18(b) and (e), with the horizontal output half that of the vertical. To increase the horizontal winding output, the amp-turns of the track need to be increased. However, simply increasing the current will increase the output from both coils proportionally, so an alternative approach is to change the location of the track conductors to improve the horizontal flux component based on a recent design for charging EV's [130] that creates a polarized pad with north and south poles and a horizontal field.

5.5.4 Double Conductor Repeated Single Phase Track

The double conductor repeated single phase track layout is constructed in a similar layout to a standard repeated track, with the loops moved together (Figure 5-16a) and the polarity in alternating loops inverted (Figure 5-17). A meander configuration may also be used to allow a single inverter to be used (Figure 5-16b), but the track cables cross each other at the ends of each loop which may lead to mounting difficulties. The adjacent track conductors
effectively double the amp turn product of the track at this location, in order to improve the horizontal field component captured and balance the output of the pickup coils.

![Double conductor repeated single phase (a) and double conductor meander (b) track configurations.](image1.png)

**Figure 5-16:** Double conductor repeated single phase (a) and double conductor meander (b) track configurations.

![Double conductor repeated single phase track current polarity.](image2.png)

**Figure 5-17:** Double conductor repeated single phase track current polarity.

In a practical system, the track conductors must have sufficient cross sectional area for the rated track current, and the resulting cable diameter restricts the spacing between the adjacent cables. Additionally, the cable insulation and any supporting material will add further thickness to the cable. Typically, a Litz cable of approximately 15mm diameter is used for track currents of 125A, as simulated in this section. As a result, a spacing of 20mm is modelled between adjacent cables. Both 100mm and 120mm track spacing is modelled for three track repetitions, shown in Figure 5-19(a-c) and Figure 5-19(d-f) respectively.

From the results shown in Figure 5-19(c), the two adjacent conductors with the associated doubling of the track amp-turns do increase the output of the horizontal coil. However, the central two pairs of conductors also double the amp-turns of the vertical coil for the region between ±50mm. This produces a peak when the pickup is centred on the track, and is clearly evident in Figure 5-19(c). The effect is not as pronounced when the optimal track spacing is used in Figure 5-19(f), and the resulting $S_U$ is reasonably constant for an offset of ±100mm. This lateral tolerance is less than the previous evenly spaced meander track, but both the $V_{OC}$ and $I_{SC}$ of the pickup are doubled, allowing a power rating 4 times greater.

To avoid simply increasing both the vertical and horizontal components simultaneously when the pickup is centred on the track due to the increase in amp-turns, a similar track configuration is modelled but with only two repetitions (shown in Figure 5-20). When the pickup is centred, the horizontal component is at a peak. Here the effect of the parallel track conductors can be seen, increasing the $V_{OC}$ and $I_{SC}$ of the horizontal coil. Both the vertical
and horizontal $I_{sc}$ components are now balanced, particularly with a track spacing of 120mm (Figure 5-20e). An $S_u$ of 700VA can be maintained, the same as that in Figure 5-19, but over a smaller range of ±50mm.

For the pickup design considered in this work, as evaluated earlier, this double conductor arrangement is best used with the optimal track spacing of 120mm, otherwise the variation in output is still large. The main advantage of this track configuration is that both the $V_{oc}$ and $I_{sc}$ of the pickup is double that when operating on the evenly spaced meander track, albeit with a reduction in lateral tolerance.
Figure 5-18: $V_{OC}$, $I_{SC}$ and $S_U$ results for the full scale pickup on a 6 wire repeated single phase track with a track spacing of; (a-c) 100mm, and (d-f) 120mm.
Figure 5-19: $V_{OC}$, $I_{SC}$ and $S_U$ results for the full scale pickup on a 6 wire double conductor repeated single phase track with a track spacing of; (a-c) 100mm, and (d-f) 120mm.
Figure 5-20: $V_{oc}$, $I_{SC}$ and $S_U$ results for the full scale pickup on a 4 wire double conductor repeated single Phase track with a track spacing of; (a-c) 100mm, and (d-f) 120mm.
5.6 Conclusions

Previously, track layouts such as meander or poly-phase tracks have been used to extend the lateral range over which pickups can deliver power, but have traditionally been used with flat pickup designs. The benefit of using the quadrature pickup on these tracks is that both magnetic field components are captured, eliminating any null points in the output power profile and increasing the power delivered by the pickup.

In order to rapidly assess different track configurations, magnetic superposition has been utilized in this chapter. The pickup needs only to be simulated over a single track conductor, and using vector summation, the track can be modelled by adjusting for the current, phase and location of each track conductor.

The best pickup output is gained when the quadrature pickup is used on an evenly spaced poly-phase track. In this chapter, a three phase bipolar track was simulated. The quadrature pickup did not increase the lateral tolerance achieved compared to a flat pickup on the same track, but instead doubled the power delivered. By increasing the track conductor spacing, the lateral range can be increased, with an associated drop in power. This allows for the system to be designed for the desired pickup output and range, whilst maintaining a consistent output power.

The meander track provides a simple means of increasing the lateral range of a pickup on a single phase system, but traditional pickups capturing one magnetic field component contain null points in the output power profile. The quadrature pickup eliminates this on both the evenly spaced and double conductor meander tracks. The evenly spaced meander track increases the range of the pickup, while the double conductor meander track increases the power delivered, with little effect on the range. The conductor spacing on both tracks is fairly restricted, with an optimal distance of 120mm for the pickup modelled.

A somewhat surprising result is how similar the output profile of the quadrature pickup is when operating on the double conductor repeated single phase track with 6 conductors or on a three phase bipolar track with 40mm conductor spacing. As poly-phase tracks require extra compensation for the mutual inductance between phases, the single phase layout may be preferred for many applications, despite the limitations on the conductor spacing. A full comparison between track layouts with the same number of conductors is presented in the following chapter, where the impact on the entire IPT system is considered.
6 Comparison of Multi-conductor Track Layouts

6.1 Introduction

In the previous chapter, the quadrature pickup was modelled over a variety of tracks which extend the lateral range of the pickup. These configurations were compared based purely on the output of the pickup. Surprisingly, the double conductor repeated single phase track has a similar output power profile to the three phase bipolar track with certain track spacing. However, the optimal track spacing for the single phase track is restricted by the pickup structure, whereas the three phase track spacing is flexible, trading output power for lateral tolerance as the spacing increases. Deciding between these track configurations must be based on not just pickup output, but the impact on the power supply.

This chapter investigates the impact on the entire IPT system when operating the quadrature pickup on the track layouts presented in the previous chapter. A comparison is made between tracks with the same number of conductors; both 4 wire and 6 wire.

In order to assess the relative costs of each system, the tracks are driven by an identical number of synchronised inverters. The required rating of these inverters is determined from the impedance reflected due to the added ferrite in the pickup, the tuning topology used, and the impact of the track layout on the reflected impedance.

Additionally, the overall track width and the cost of any track compensation required is also considered. Based on these factors, the track most suitable for extending the lateral range of pickup movement for AGV systems can be found.

6.2 Comparison of 6 Wire Systems

The results from the previous chapter show a clear advantage to using a quadrature pickup on all the different track types. Capturing both horizontal and vertical components eliminates any null points in the power profile, and increases the power in poly-phase systems. However, many of the results above are similar, and a comparison is needed to decide the best track configuration to use.
In assessing each system, if similar power profiles can be delivered by the pickup, one of the deciding factors is cost. Therefore, given the track current per phase and the frequency of operation in each system is identical in all comparisons (given in Table 6-1), tracks with the same number of conductors are compared against each other, as the volume of copper is the primary cost of the track, while the VA rating of the inverter (as indicated by the loading which it must drive) is the key cost for the supply.

### Table 6-1: Simulation Conditions

<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track Current</td>
<td>125A</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>38.4kHz</td>
</tr>
<tr>
<td>Track Spacing</td>
<td>Varies</td>
</tr>
<tr>
<td>Track Diameter</td>
<td>8mm</td>
</tr>
<tr>
<td>Pickup Ferrite</td>
<td>4 x 2</td>
</tr>
<tr>
<td>(See Figure 3-8)</td>
<td>200mm</td>
</tr>
<tr>
<td>Horizontal Turns</td>
<td>39</td>
</tr>
<tr>
<td>Vertical Turns</td>
<td>30</td>
</tr>
<tr>
<td>Pickup Height</td>
<td>20mm</td>
</tr>
</tbody>
</table>

#### 6.2.1 Pickup Output

The first comparison is for tracks with six conductors, where the pickup has a power profile of 500VA over ±100mm, as shown in Figure 6-1. The evenly spaced three phase bipolar track with 60mm and 80mm conductor spacing is compared to the double conductor repeated single phase track (abbreviated to DC rep 1ph). On the latter track, the track spacing is restricted to 120mm, which is optimal for the pickup used.

![Figure 6-1: $S_u$ comparison between the three phase bipolar track and the 6 wire double conductor repeated single phase track.](image)
From Figure 6-1, the three phase bipolar track appears to hold a small advantage in the $S_U$ delivered by the pickup. However, there is a strong correlation between the three phase track and the double conductor tracks. Both deliver approximately 700VA over a range of ±100mm (the three phase delivers 730VA). The small difference is easily compensated for with tuning.

If designing the track purely for the pickup output, the three phase track is preferable due to the increased $S_U$. Another advantage is that the track spacing can easily be changed to increase either the lateral tolerance or $S_U$ of the pickup, whereas the conductor spacing for the double conductor track is restricted by the pickup design (120mm for this pickup). However, the following comparison is based on the cost of the complete IPT system.

### 6.2.2 Track Compensation and Implications

In this comparison, tracks with six conductors are compared to each other. For a fair comparison, each of these track configurations is implemented using three individual track loops, each driven by a synchronised inverter either in phase for the single phase system, or 120 degrees separated for the three phase system. These inverters can then be directly compared, as discussed following. While the track loops are set to the same length, the individual loops in the three phase bipolar track are 180mm, wider than the 120mm loops of the double conductor repeated single phase track. The resulting track inductance of the three phase track will be greater (approx. 10%, given by $L(\mu H) \approx \frac{L}{\pi} \ln \left(\frac{d}{r}\right)$). As each inverter is considered identical for this comparison, the track inductance must be similar. Either shorter tracks must be used, or additional series compensation is needed to overcome this increased inductance.

However, as previously mentioned, further compensation is also necessary to balance the mutual coupling between track phases in poly-phase systems [24, 129], adding additional cost compared to the double conductor track, which does not require such compensation. For a straight track such as those presented, the preferable solution is to use flux compensation using mutually coupled gapped toroids [24, 129]. The disadvantage of this is that considerable inductance is added to the track. As before, shorter tracks or additional series compensation is needed to overcome this inductance. For this comparison, series compensation is used so that both tracks are the same length and use similar amounts of copper (representing cost). Both the mutually coupled gapped toroids and the additional series compensation represent a significant cost to the three phase track. In comparison, the double conductor single phase system does not require this compensation.
Another factor that needs to be considered is the overall track width. While this does not directly affect the cost of the IPT system, in some applications the space for laying the track may be limited, especially for tracks extending beyond the lateral range that rated power is delivered. In this comparison, the three phase track has an overall track width of 300mm, and the double conductor single phase track is 400mm wide. In both cases, the track conductors extend beyond the rated lateral tolerance of ±100mm (based on uncompensated power). If the overall track width is important in the intended application, the three phase track is preferable. As previously mentioned, the three phase track width can also be freely adjusted, whereas the double conductor single phase track is limited based on the pickup design.

6.2.3 Inverter Loading

For a fair comparison, the track layouts are implemented using three separate track loops operating with identical current magnitudes at identical frequency as outlined earlier. This allows three identical inverters to drive each loop, synchronised either in phase for the double conductor system shown in Figure 6-5(a), or 120 degrees out of phase for the three phase system, shown in Figure 6-3. In doing so, the power and VAR loading of each inverter can be directly compared. Alternatively, both track layouts can be implemented using a single power supply; the three phase track using the inverter described in [24, 131], and the double conductor single phase track using the meander arrangement presented in the previous chapter, shown in Figure 6-5(b). The power supply driving this meander track can be implemented using paralleled inverters (Figure 6-5b), and a direct comparison can be made. This is not possible with the three phase system driven by a single power supply.
Previous research into flat pickups operating over three phase tracks show that the pickup reflects an uneven loading both real and reactive between the track phases as it moves across a poly-phase track [24, 131]. This requires that each phase of the inverter is rated to deliver the required power to the pickup, and handle any VAR loading that is present. This is also true of the quadrature pickup on poly-phase tracks, with the added complication of two tuned coils reflecting a reactive load onto the track.

The techniques described in [24, 131] are used to calculate the loading on the track due to the pickup, taking into account that the load on the pickup is shared between the two coils based on the ratio of the Dominant Electrical Parameter (DEP) [16] contributed by each coil.
Just as the track current induces a voltage in the pickup ($V_{OC}$), the current in the pickup ($I_2$) induces a voltage in each of the track cables ($V_n$):

$$V_n = j\omega M_{n2} I_2$$  \hspace{1cm} (6-1)

As mentioned in Chapter 4, the tuning of the pickup influences the voltage reflected onto the track, based on $I_2$. This current can be found from the impedance seen by the induced voltage in the pickup, $V_{OC}$, while operating at resonance [24, 131]:

$$Z_{EQ} \big|_{\omega=\omega_0} = \begin{cases} R_{EQ} & \text{series tuned} \\ \frac{R_{EQ}}{Q_2^2 + 1} + j\frac{\omega L_2}{Q_2^2 + 1} & \text{parallel tuned} \end{cases}$$  \hspace{1cm} (6-2)

Here, $Q_2$ is the secondary quality factor, which for a parallel tuned pickup is defined as $Q_2 = \omega_0 C_2 R_{EQ}$.

To calculate the induced voltage in each track conductor, the mutual coupling of the pickup to individual track conductors is required. This is easily calculated from the pickup output profiles over a single track conductor (shown in the previous chapter) as required when using the superposition technique. This is typically expressed as $\kappa_g$ to allow the turns of each coil to be decided as required:

$$M_{n2} = \frac{N_1}{N_2} L_z \kappa_g$$  \hspace{1cm} (6-3)

Substituting (6-3) into (6-1) gives the reflected voltages in each cable:

$$V_n = j\omega M_{n2} I_2$$

$$= j\omega \left( \frac{N_1}{N_2} L_z \kappa_g \right) \frac{V_{OC}}{Z_{EQ}}$$  \hspace{1cm} (6-4)

From this, the reflected impedance can be found:

$$Z_{rn} = \frac{V_n}{I_n}$$

$$= j\omega \left( \frac{N_1}{N_2} L_z \kappa_g \right) \frac{V_{OC}}{I_n Z_{EQ}}$$  \hspace{1cm} (6-5)

The real and reactive components are then determined:
The real and reactive loading on each track conductor can then be calculated using the resistance and reactance from (6-6) and (6-7). In the case of a bipolar poly-phase track, as well as the repeated single phase track, the resulting loads calculated for each of the conductors which form a closed loop must be summed in order to represent the power delivered by each inverter. Note that (6-6) and (6-7) only consider the impedance reflected on the track conductors by the pickup coils, the pickup ferrite must be considered separately. Due to the non linear nature of the pickup ferrite, the change in inductance of the track loops cannot be calculated, but must be simulated or measured, as discussed in Chapter 4. For these comparisons, the individual loops of 120mm and 180mm were simulated in JMAG with the pickup 20mm above the track. The voltage and track current are then used to determine the change in reactance of the track (the resistance is negligible). This reactance can then be added to the reflected impedance of the coils.

To compare the 6 wire track systems described earlier in this section, the quadrature pickup is modelled to supply 2kW to a resistive load. At this rated output, the pickup operates with a $Q$ of 2.5 – 2.8 over a range of ±100mm. At ±200mm, in order to maintain an output of 2kW, a $Q$ of 10 is required from both coils, which is possible in this ideal simulation. However, in practice this represents the operational range of the pickup, as $Q$’s greater than 10 are impractical due to component tolerances and resonant losses in the pickup circuit. As such it is assumed that full rated power will not be delivered at offsets beyond this range.

### 6.2.3.1 Series Tuned Pickups

The first comparison between the track configurations is with a series tuned quadrature pickup, shown in Figure 6-6 and Figure 6-9. Each of the quadrature coils are individually tuned, and the load applied to each is determined by the $V_{OC}$ ratio between the coils as this is the DEP for series tuned pickups. The load resistors are chosen so that the resonant currents are matched, and deliver 2kW across both loads.


6.2.3.1.1  Three Phase Bipolar Track

The resulting resistive load profiles on each inverter of the three phase track are shown in Figure 6-6(a-c) for the horizontal and vertical coils, and the combined load respectively. When the pickup is centrally located between ±150mm, each inverter supplies up to 1000W, half the rated load. However, beyond these offsets, the load on the individual inverters can be as high as 1600W.

Additionally, ignoring the effect of the pickup ferrite, the reflected impedance seen by the track due to the induced voltage, $V_{oc}$ in the pickup is purely resistive. As such, any reactive loading supplied by the inverters is due only to the track layout. As expected from previous research [24, 131], the inverters supplying the three phase track experience both capacitive and inductive loading depending on the location of the pickup relative to the track, as indicated by the reactive power profiles shown in Figure 6-6(d-f). As the track currents are 120 degrees out of phase, the reflected load on each phase is separated by the same angle. This reactive loading varies as much as ±500VAR due to the operation of both the horizontal and vertical coils (Figure 6-6(d) and (e) respectively). Notably, between ±150mm offsets, the reactive loading as a consequence of operating each coil is opposite; i.e. when the loading from the horizontal coil is capacitive, the loading from the vertical coil is inductive. The result is a reduced reactive loading (only ±200VAR) over this range due to the quadrature operation, compared with the VAR loading which would otherwise be present if only a vertical or horizontal pickup were used, as shown in Figure 6-6(f). However, at pickup offsets greater than ±150mm, the VAR loading from each coil is additive, resulting in increasing reactive loads on each inverter which can be as high as ±800VAR.

It is important to note that with the series tuned pickup (and no ferrite), which presents a unity power factor, this track configuration has this VAR loading due to the phase of the track conductors. This loading is dependent on the current in the pickup coil, which is based on the load. As such, this VAR load will increase with the load on the pickup, and will vary with a different output rating.

The resulting power delivered by each inverter is shown in Figure 6-6(g-i). All three phases supply power when the pickup is within the operational range, between 500-1000VA. When the pickup operates near the edge of the track, most of the power, as high as 1700VA, is supplied by the inverter driving the outer loop. However, beyond ±200mm a $Q$ greater than 10 is required to achieve full rated power to the load. As such, the loading will be limited by the power that can be delivered past this range.
As noted earlier, the load on the inverters presented in Figure 6-6 is only due to the reflected impedance of the quadrature coils, and does not include the effect of the ferrite in the pickup. The reflected reactance of the two coils is shown in Figure 6-7(a), and the change in reactance of the track due to the ferrite is shown in Figure 6-7(b). The increase on each track loop is up to 20mΩ, primarily over the operating range of ±200mm. When this reactance is added to that of the coils, shown in Figure 6-7(c), the reflected load has an additional inductive component over the range of ±100mm. At greater offsets, the reactive load is either highly capacitive or inductive, especially on the outer track loops.

The resulting power that must be delivered is shown in Figure 6-8. The real power delivered by each inverter (shown in Figure 6-8a) is unchanged from before, as the ferrite has a negligible impact on the resistance of the track. However, with the added reactance on the track due to the ferrite, each inverter must now provide up to an additional 350VARs over the operating range of ±100mm. Beyond ±150mm, the reactance on the outer phases is significant: Inverter 1 must supply an inductive load greater than 800VA, while Inverter 3 must supply a capacitive load of 700VA. This results in an increase in the total power that needs to be delivered by each inverter, shown in Figure 6-8(c) and consequently a significant increase in its rating if operation is allowed in this range. Of importance is the power requirement from each inverter between ±150 – 200mm, which is between 1000 – 1750VA. While this lies at the edge of the range where the pickup is likely to reach full power, the large reactive load is likely to exceed the ratings of the inverter.
Figure 6-6: (a-c) Real, (d-f) reactive and (g-i) total power supplied by each inverter to the horizontal, vertical and combined coils of a series tuned quadrature pickup operating at 2000W above a three phase bipolar track with 60mm conductor spacing.
Figure 6-7: Reactance on the track due to (a) both coils operating, (b) the ferrite, and (c) the total reactance due to a series tuned quadrature pickup operating at 2000W above a three phase bipolar track with 60mm conductor spacing.

Figure 6-8: (a) Real, (b) reactive and (c) total power supplied by each inverter to a series tuned quadrature pickup (including ferrite effect) operating at 2000W above a three phase bipolar track with 60mm conductor spacing.
6.2.3.1.2 **Double Conductor Repeated Single Phase Track**

The results of the double conductor repeated single phase track are shown in Figure 6-9. Unlike the quadrature pickup on the three phase track, at a number of offsets the load is powered completely by one of the pickup coils, as shown in Figure 6-9(a) and (b). This is due to the null points in the individual coil power profiles when operating on single phase tracks. Also, the load is not shared as well between the inverters powering the track. When the pickup is operated on the track between ±150mm, two of the three inverters must supply approximately 1300W, while the third has no load. For offsets greater than ±150mm, the full power is supplied by one inverter. In fact, beyond ±200mm the power requirement from the supply exceeds the rated power requested by the pickup, and can be as high as 2400W, with the excess 400W feeding back into the central inverter. This occurs in this simulation as only the reflected voltages on the track are considered, and the inverters are considered ideal and can sink current as well as source current. Practically this can only occur if the inverters share a common DC bus, or they are designed with reversible rectifiers to feed current back to the mains. As before, the pickup is assumed to be unable to operate at full rated load due to limits on operational $Q$ beyond ±200mm, and as such the real load to each inverter will be reduced here compared to this ideal situation.

The key difference between this track layout and the three phase track is that no reactive loading is presented to the individual inverters when supplying a series tuned pickup (provided the pickup load is resistive), as shown in Figure 6-9(d-f). This is because the inverters are in phase, and the series tuned pickup reflects unity power factor. As no VAR loading is presented to the inverters, the total load each inverter must supply is equal to the real power, as shown in Figure 6-9(g-i). However as discussed earlier, this does not consider the reactance due to the ferrite.

The change in reactance of the track due to the ferrite is shown in Figure 6-10(b), and as the reflected reactance of the coils is zero for all offsets, this gives the total reactance on the track in Figure 6-10(c). The reactance on each track loop is 16mΩ, and is always inductive. This reactance gives a VAR load of 200VAR on each inverter, shown in Figure 6-11(b). As such, the total power delivered by each inverter, shown in Figure 6-11(c) is slightly increased due to the ferrite.

As this reactance due to the ferrite is fairly constant for applications where there are a known number of AGV’s operating continuously on a track while it is powered, it can be compensated for when tuning the track by reducing the track inductance by the average
amount added by the pickup ferrite (multiplied by the number of pickups expected to be operating continuously on that section of track). Practically, this is done by tuning the track to the required value with the pickups in situ. When the pickups are not present on a track loop so tuned, the track appears capacitive.

Alternatively, the reactance added by the ferrite can be compensated for with a parallel tuned pickup. The loading on the track layouts operating with a parallel tuned pickup is shown in the following section.
Figure 6-9: (a-c) Real, (d-f) reactive and (g-i) total power supplied by each inverter to the horizontal, vertical and combined coils of a series tuned quadrature pickup operating at 2000W above a 6 wire double conductor repeated single phase track with 120mm track spacing (20mm between double conductors).
Figure 6-10: Reactance on the track due to (a) both coils operating, (b) the ferrite, and (c) the total reactance due to a series tuned quadrature pickup operating at 2000W above a 6 wire double conductor repeated single phase track with 120mm track spacing (20mm between double conductors).

Figure 6-11: (a) Real, (b) reactive and (c) total power supplied by each inverter to a series tuned quadrature pickup (including ferrite effect) operating at 2000W above a 6 wire double conductor repeated single phase track with 120mm track spacing (20mm between double conductors).
6.2.3.2 Parallel Tuned Pickups

The second comparison between the track configurations is with a parallel tuned pickup, shown in Figure 6-12 and Figure 6-15. The load on the quadrature coils is determined by the $I_{sc}$ ratio between the coils, as this is the DEP for parallel tuned pickups. However, there is only a slight difference to the resistive load profiles on each inverter, shown in Figure 6-12(a-c) and Figure 6-15(a-c) compared to those with a series tuned pickup.

6.2.3.2.1 Three Phase Bipolar Track

The critical difference between this and the series tuning topologies used previously is the reflected impedance seen on the track due to the $V_{oc}$ of the parallel tuned pickup. Here it is capacitive. As previously mentioned in Chapter 4, this is of benefit in AGV systems, as this capacitance cancels the added inductance seen as the pickup ferrite moves onto the track. Similar to the series tuned pickup modelled previously, when operating on a three phase track, the reactive loading on the inverters from each coil of the parallel tuned quadrature pickup varies, and can be either capacitive or inductive depending on the location of the pickup, as shown in Figure 6-12(d) and (e). Compared with previous results, both systems see a load which is more capacitive on average, and is shown in the combined reactive load in Figure 6-12(f). Over a range of ±150mm, the loading varied from 0 – 500VAR, however beyond this the reactive loading is as large as ±800VAR. The total power supplied by each inverter is only slightly higher compared with the series tuned pickup operating on the same track. This is evident in the total power delivered by all inverters shown in Figure 6-12(g-i).

The real advantage to the parallel tuning topology is seen when we consider the reactance of the pickup ferrite, shown in Figure 6-13(b). When this is added to the reflected reactance on the track due to the pickup coils, shown in Figure 6-13(a), the result is primarily a capacitive reactance between the operating range of ±150mm, ranging between -20 – 5mΩ (Figure 6-13c). This results in a VAR load of -250VAR on each track loop, shown in Figure 6-14(b). This is lower than the series tuned pickup on the same track, and is also capacitive on the track. Due to the LCL topology commonly used in current power supplies, this appears inductive to the inverter, which is preferable [120, 128].

6.2.3.2.2 Double Conductor Repeated Single Phase Track

For the parallel tuned quadrature pickup operating on the double conductor repeated single phase track, the inverters do experience a capacitive load, shown in Figure 6-15(d-f). This is due solely to the impedance of the pickup, not the track layout (as investigated with the
series tuned pickup in Figure 6-9). Each inverter must supply a reactive load between 0 – 500VAR over the range of ±150mm. Unlike the three phase track, beyond these offsets the reactive loading reduces to zero. As the pickup moves across the track, this VAR loading is less variable.

The VAR loading occurs when the pickup is mostly coupled to the track loop driven by an individual inverter, which is also where that track loop inductance is increased due to the ferrite in the pickup. For example, inverter 1 must supply a VAR load between -300 – 50mm offset range, as shown in Figure 6-15(f), where the track conductors for that loop are located at -200mm and -80mm. This is shown in Figure 6-16(b), where the reactance on each track loop due to the pickup ferrite occurs at the same locations as the reflected impedance of the coils from Figure 6-16(a), but with opposite polarity. The combined reactance is a slightly capacitive reactance of -20mΩ, and is more consistent with lateral pickup offset, as shown in Figure 6-16(c). This results in a VAR load of -300VAR capacitive, shown in Figure 6-17(b). While slightly higher than for the three phase track, the smoothness of the VAR loading profile on each inverter is preferable to the variation shown on the three phase track in Figure 6-14(b). Furthermore, when the double conductor meander single phase track is driven with paralleled inverters, the total VAR load is intrinsically shared equally between all three inverters [132].

One important point to note in this comparison is that the VAR loading on the double conductor repeated single phase track is due to the ferrite and the coil tuning, which both remain constant regardless of the load on the pickup. The VAR loading on the three phase bipolar track is also dependant on the reflected impedance due to the phase difference between track conductors, which increases with the load as discussed previously. This comparison has been made at the rated 2kW, which is representative of commercial pickups and a worse case condition for a 2kW pickup operating within its ratings. For a pickup chosen to operate at a higher load, the conclusion from this section may be different.

Comparing these two track configurations, it is clear that the double conductor repeated single phase track has an advantage in terms of the VAR loading on the track loops. The series tuned pickup coil operates at unity power factor, and reflects no VAR load to the track. However the ferrite in the pickup introduces a VAR load of 200VA, and has a smooth VAR profile centred around the track loops, which can easily be compensated for. With parallel tuning on the secondary, the resultant VAR profile is capacitive. This is preferable as this appears inductive with the inverter bridge due to the power supply LCL topology.
The three phase track does have a slight advantage load sharing between the three inverters compared to a single phase system that is operating with individual inverters for each track loop. At any location, all three inverters contribute power, whereas only two inverters contribute with the double conductor repeated single phase track. However, when the single phase system is driven with paralleled inverters, and the track arranged in a single meander loop, the total load on the track is equally shared between all three inverters [132]. As the total load on both the three phase and single phase tracks are similar, the inherent load sharing of the paralleled inverters driving the double conductor repeated single phase track is the preferred system.
Figure 6-12: (a-c) Real, (d-f) reactive and (g-i) total power supplied by each inverter to the horizontal, vertical and combined coils of a parallel tuned quadrature pickup operating at 2000W above a three phase bipolar track with 60mm conductor spacing.
Figure 6-13: Reactance on the track due to (a) both coils operating, (b) the ferrite, and (c) the total reactance due to a parallel tuned quadrature pickup operating at 2000W above a three phase bipolar track with 60mm conductor spacing.

Figure 6-14: (a) Real, (b) reactive and (c) total power supplied by each inverter to a parallel tuned quadrature pickup (including ferrite effect) operating at 2000W above a three phase bipolar track with 60mm conductor spacing.
Figure 6-15: (a-c) Real, (d-f) reactive and (g-i) total power supplied by each inverter to the horizontal, vertical and combined coils of a parallel tuned quadrature pickup operating at 2000W above a 6 wire double conductor repeated single phase track with 120mm track spacing (20mm between double conductors).
Figure 6-16: Reactance on the track due to (a) both coils operating, (b) the ferrite, and (c) the total reactance due to a parallel tuned quadrature pickup operating at 2000W above a 6 wire double conductor repeated single phase track with 120mm track spacing (20mm between double conductors).

Figure 6-17: (a) Real, (b) reactive and (c) total power supplied by each inverter to a parallel tuned quadrature pickup (including ferrite effect) operating at 2000W above a 6 wire double conductor repeated single phase track with 120mm track spacing (20mm between double conductors).


6.2.4 Summary

The choice between the two track layouts discussed in this chapter must be based on all aspects of the system: the pickup output, track compensation, and inverter loading. The advantages of each system are summarised in Table 6-2.

The spacing of the conductors in each track layout was chosen such that the outputs of the quadrature pickup on the two tracks were similar and the track loops for each system were set to the same length. The three phase track does have a smaller overall track width for the same lateral tolerance, and the track spacing can be varied to adjust the power and lateral range. However, the individual track loops in the three phase track are wider, resulting in a higher track inductance. Additionally, the compensating toroids to cancel the mutual coupling between track phases add a significant inductance to the track. Instead of shortening the track, series compensation is used, such that the cost of the track and the number of pickups that can operate on a track is kept equal. None of this is required on the double conductor repeated single phase track, so this clearly has a cost advantage in track cost.

<table>
<thead>
<tr>
<th>Track Layout</th>
<th>Track Cable</th>
<th>Flexible spacing</th>
<th>Overall Track Width</th>
<th>Mutual Compensation</th>
<th>Tuning C</th>
<th>Inverter</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 phase bipolar</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Required</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>Double conductor repeated single phase</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>N/A</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Double Conductor Meander with Paralleled Inverters</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>N/A</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

The critical difference between the two systems is the VAR loading on the tracks with the quadrature pickup operating. This is caused by the pickup ferrite and the tuning used on the pickup, both of which remain constant regardless of load. This constancy is present for both track layouts. Additionally, the three phase track has further VAR loading due to the phases of the tracks. This varies with the current in the pickup, and hence varies with the load supplied by the pickup. The result is that the double conductor repeated single phase track operating with the parallel tuned pickup offered the best VAR profile; it is a smooth profile with a slightly capacitive load located at each track loop (which appears inductive to the inverter).

Furthermore, when the double conductor repeated single phase track is driven with paralleled inverters, as opposed to individual inverters driving each loop, the overall load
(including the VAR load) is equally distributed between all three inverters. In comparison, the load sharing between inverters with the three phase system is similar but not as effective, and in the case of the repeated single phase track with individual inverters, the load is only shared between two inverters at various pickup locations.

It is clear that for the majority of applications, where cost is the deciding factor, the double conductor repeated single phase track is the preferable track layout. Ideally this is driven with paralleled inverters to achieve good load sharing between inverters. The cost of the additional toroids, tuning capacitors and VAR loading restrict the use of the three phase track for AGV systems to scenarios where the quadrature pickup cannot be used.

### 6.3 Comparison of 4 Wire Systems

A second comparison is for systems with four wires. Here a double conductor repeated single phase system with 120mm track spacing, shown in Figure 6-18, is compared to a two phase bipolar track with 120mm track spacing and 0.29 overlap, shown in Figure 6-19. It is clear that the double conductor system couples a greater power to the pickup, and can deliver 700VA over a range of ±50mm, as shown in Figure 6-20. The two phase system delivers approximately 60% the power over the same range. Most of the advantages from Table 6-2 exist in this comparison, however, the 0.29 overlap is an alternative compensation for the mutual coupling between track conductors. As such, the toroidal compensation, and hence a large proportion of the series capacitance is not required, reducing cost.

![Figure 6-18](image-url)

Figure 6-18: (a) Individual inverters supplying each loop of a double conductor repeated single phase track, and (b) paralleled inverters supplying a double conductor meander single phase track – inverters synchronised in phase.
Chapter 6  Comparison of Multi-conductor Track Layouts

Figure 6-19: Individual inverters supplying each phase of a two phase bipolar track with 0.29 overlap – inverters synchronised 90 degrees out of phase.

Figure 6-20: $S_U$ comparison between a 4 wire double conductor repeated single phase track to a two phase bipolar track with 0.29 overlap.

Additionally, the total loading on each of these tracks are shown in Figure 6-21 and Figure 6-22. This includes the loading from the coils and the ferrite as the pickup moves across the tracks. The VAR load on the two phase track is quite undesirable, with a capacitive load on one inverter and an inductive load on the other, reaching ±300VAR over the ±50mm operating range as shown in Figure 6-21(b). In comparison, the VAR load on the double conductor repeated single phase track is a smooth capacitive load profile of -200VAR per track loop. The overall power required by each is comparable over the operating range, with a maximum of 1300VA shown in Figure 6-21(c) and Figure 6-22(c). With the reduction in $S_U$ and the extra VAR loading, it is clear that the double conductor repeated single phase track is preferable for tracks with 4 conductors.
Figure 6-21: (a) Real, (b) reactive and (c) total power supplied by each inverter to a parallel tuned quadrature pickup (including ferrite effect) operating at 2000W above a two phase bipolar track with 120mm track spacing and 0.29 overlap.

Figure 6-22: (a) Real, (b) reactive and (c) total power supplied by each inverter to a parallel tuned quadrature pickup (including ferrite effect) operating at 2000W above a 4 wire double conductor repeated single phase track with 120mm track spacing (20mm between double conductors).
6.4 Conclusions

The previous chapter presented a number of multi-conductor track layouts to extend the power profile of the quadrature pickup. Here a comparison is made between layouts with a similar number of conductors. The pickup output, track compensation and inverter loading are all considered.

Firstly, two track layouts with six conductors were compared; the 3 phase bipolar track with 60mm conductor spacing, and the double conductor repeated single phase track with 120mm spacing. The quadrature pickup has a similar uncompensated power profile when operating on either track. The track spacing may be varied with the three phase track, offering flexibility, where the double conductor track is inherently limited by the pickup structure. Additionally, the three phase track is narrower overall, while allowing the same lateral range.

However, the three phase track requires the addition of toroidal ferrites to compensate the mutual inductance that occurs between phases. This adds significant inductance to the track. Exacerbating this, the area within individual track loops is larger than the double conductor track, and hence the inductance is larger still. To compensate this added inductance, a shorter track, or series compensation must be used, with additional cost.

The most significant factor is the loading on each track loop from a quadrature pickup. This comparison was undertaken here for a system rated for and operating at a full 2kW load. The reflected impedance on each wire due to the pickup was then calculated. The increase in track inductance as the pickup ferrite moves across the track was also considered. The inductance due to the ferrite can be (over)compensated by the reflected reactance when parallel tuning is used, whereas the series tuned quadrature pickup does not reflect this reactance and remains inductive. This reactive load remains constant regardless of the load on the pickup.

The three phase track has a further VAR loading due to the phase of the track currents. The VAR loading is present regardless of the pickup tuning. Each phase varies both capacitively and inductively depending on the pickup location (the vector summation remains zero), leading to a varying VAR profile across the track. This is proportional to the load on the pickup, as the reflected impedance is due to the current in the pickup coils.

Because of the larger and varying VAR load on the track loops and the additional track compensation required with the three phase track, the double conductor repeated single phase is the preferred track layout for AGV systems. The optimal system is when this track is
formed with a single track loop in a meander arrangement, and driven by multiple paralleled inverters (or a single large inverter). This provides even load sharing between the inverters irrespective of the pickup position above the track.

A further comparison was made of four wire track layouts; the 2 phase bipolar track with 120mm spacing and 0.29 overlap, and the double conductor repeated single phase track. Most of the issues from the six wire comparison still exist, however the 0.29 overlap is an alternative compensation for the mutual inductance between tracks. As such, the toroidal compensation and additional series capacitance is not required. However, the uncompensated output of the pickup is lower on the two phase track. Because of this, the double conductor repeated single phase track is also preferable for tracks with four conductors, and a significant improvement.

For the majority of applications, where cost is the deciding factor, the double conductor repeated single phase track is the preferable track layout. The cost of the additional toroids, tuning capacitors and VAR loading restrict the use of the multi-phase track systems for AGV's.
7 Tightly Coupled High Power Pickups

7.1 Introduction

One issue surrounding the design of high power IPT pickups for commercial use is that as the pickups are scaled up, and track current is increased to transfer greater power, the voltages within the pickup exceed levels set by various safety standards. To lower these voltages, the number of turns on the pickup coil must be reduced. However, this comes at a cost, namely a reduced coupling factor as the winding covers less of the pickup. Multiple strands or ribbon Litz can help maintain a good coupling, but this adds significant cost and complexity.

The primary goal in designing the coaxial pickup is to design a high power pickup at low cost. In existing pickups, the large cost is in the ferrite and the Litz wire. To reduce cost, the coaxial pickup uses a copper pipe as the coil surrounded by a toroidal ferrite, which is readily available and does not require a custom ferrite shape to be produced. This also has the advantage of having a high coupling factor with the track, which is highly desirable for high power pickups.

This chapter covers the magnetic design of a coaxial pickup intended for use at high power levels approaching 100kW. This is investigated through simulation and practical measurements. Two conceptual controllers are also presented to boost and regulate the output voltage of the pickup to industrial levels. Brief insights into these controllers are presented, but a full investigation of these is beyond the scope of this thesis.

7.2 Previous Research

Ideally the coaxial pickup would be constructed with complete toroids for optimal coupling as used in coaxial transformers, shown in Figure 7-1(a). However, as the design is for a pickup which is able to move along a track, this is not possible, as any practical track requires mechanical supports, which will interfere with the pickup movement.

Previous research in this area focussed on a pickup designed with hinged toroidal halves (Figure 7-1(c)), similar to a current transformer probe [77]. This allows removal from the track, and movement over track supports. Practically, some mechanism is required for the
hinged toroids to open when travelling over track supports, and the toroids will require a protective material to cover the fragile ferrite, adding an effective air gap in the flux path. If a mechanical system is employed to separate the toroid halves, material wear is likely to result. As one of the intended applications is in clean room systems, debris from mechanical wear is problematic, so the hinged toroid design is not suitable.

![Diagram of toroid designs](image)

**Figure 7-1: Coaxial Pickup designs; (a) ideal, (b) slotted toroid, (c) hinged toroid**

This chapter focuses on a slotted toroid design Figure 7-1(b), also suggested in [76, 77]. The C-Core or slotted toroid does not completely encapsulate the primary winding, and allows for supports to hold this winding. The gaps in the toroid must be designed to allow for these supports, and the desired movement range of the pickup. In previous research [76, 77], this slotted design was rejected because of the increased leakage inductance which is prohibitive to the pickup circuitry used, which consisted only of a rectifier, with no regulation on the secondary side. Any regulation could only occur on the primary side, and so only one secondary could operate at once. The design in this chapter varies from the previous research by tuning the secondary pickup, and regulating on the secondary side. This allows a design with a higher leakage inductance, such as the slotted toroid design, and multiple pickups to operate on a track.

### 7.3 Magnetic Design

#### 7.3.1 Small Coaxial Pickup

To investigate the feasibility of the coaxial pickup, simulations were carried out using 3D JMAG magnetic modelling software. Primary investigations were carried out to see what the open circuit voltage and short circuit current characteristics of the pickup were. A small scale pickup (Figure 7-2) was simulated with the dimensions in Table 3-3. Initial results are presented in Figure 7-3 for this pickup operating on a primary track having a track current of 100A RMS at 38.4 kHz.
Figure 7-2: Small coaxial pickup design

Table 7-1: Small Coaxial Pickup Dimensions

<table>
<thead>
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<th>Pickup Shape</th>
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</thead>
<tbody>
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</tr>
<tr>
<td>Toroid Inner Diameter</td>
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</tr>
<tr>
<td>Toroid Length</td>
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</tr>
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<td>Toroid Slot Width</td>
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</tr>
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<td>Copper Pipe Slot Width</td>
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</tr>
<tr>
<td>Toroid Spacing</td>
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</tr>
<tr>
<td>Number of Toroids</td>
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</tr>
</tbody>
</table>

Figure 7-3: Simulation results of the small coaxial pickup with an increasing number of toroid pairs; (a) $V_{OC}$ and (b) $I_{SC}$.

The $V_{OC}$ of a typical pickup is linear with respect to length, however at very short lengths the voltage is expected to drop to zero [16]. If a straight line was drawn through the linear region of the $V_{OC}$ curve, the y-axis intercept would be greater than zero. This is due to what is
The $I_{SC}$ of any pickup is also expected to approach an asymptotic maximum as the pickup length is increased. However, in Figure 7-3(b), it can be seen that the $I_{SC}$ drops more than expected at short lengths, whereas the voltage remains linear. This can be explained by looking at the inductance of the pickup, as shown in Figure 7-4. As shown, a linear relationship exists between the number of toroids and the pickup inductance. With no pickups, a significant inductance of 28nH still exists. This is the inductance due to the copper pipe itself and the end connections. The coaxial pickup has a single turn copper winding and this inductance is comparable to the inductance due to the toroids when a low number of toroids are used, giving rise to the current profile of Figure 7-3(b).

![Figure 7-4: Simulated inductance of the Small coaxial pickup](image)

One of the notable aspects of this pickup is the high coupling. Normally pickups used in material handling applications have a $\kappa_{\phi}$ of 0.3 – 0.7. This pickup however has a $\kappa_{\phi}$ of 0.92 when the pickup is built with 10 toroid pairs. This good coupling is due to two factors, the copper pipe pickup and ferrite surrounding the majority of the track, and a low Inter Conductor Cancellation Factor, ICCF [16, 72]. The ICCF of a pickup structure increases when flux from one track conductor opposes the flux from a second track conductor within the pickup ferrite, and is determined by the shape of the ferrite. Pickup designs such as H and S-pickups reduce this effect and even use it as an advantage. The coaxial pickup minimises this by using toroidal ferrites and an air gap between the toroids on each pipe, increasing the reluctance path for the flux that contributes to the ICCF.

### 7.3.2 Full Scale Coaxial Pickup

For the large scale pickup, a variety of toroids were considered. Initial simulations were carried out on a design using larger dimensional toroid from the same manufacturer which supplied those used in the small scale model, the dimensions of which are given in Table
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7-2. This was simulated with a 300A track current at 38.4kHz. The resulting $V_{oc}$ and $I_{sc}$ can be seen in Figure 7-6.

Figure 7-5: Large coaxial pickup design.

Table 7-2: Large Coaxial Pickup Dimensions

<table>
<thead>
<tr>
<th>Pickup Shape</th>
<th>5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroid Outer Diameter</td>
<td>85mm</td>
</tr>
<tr>
<td>Toroid Inner Diameter</td>
<td>55mm</td>
</tr>
<tr>
<td>Toroid Length</td>
<td>16mm</td>
</tr>
<tr>
<td>Toroid Slot Width</td>
<td>25mm</td>
</tr>
<tr>
<td>Copper Pipe Slot Width</td>
<td>29mm</td>
</tr>
<tr>
<td>Toroid Spacing</td>
<td>3mm</td>
</tr>
<tr>
<td>Number of Toroids</td>
<td>16</td>
</tr>
</tbody>
</table>

Figure 7-6: Simulation results of the large coaxial pickup with an increasing number of toroid pairs; (a) $V_{oc}$ and (b) $I_{sc}$.  

The simulated toroids have proven to be difficult to source, so toroids of similar dimensions were used, and simulated results of these are presented later along with measured results. Large IPT power supplies are normally limited in operating frequency, thus an operating frequency of 38.4kHz is impractical at this power level. The track frequency has instead been reduced to 20 kHz to coincide with power supplies that are commercially available. Reducing the frequency has the effect of reducing the open circuit voltage of the pickup. The pickup is also intended for use at 10kHz given industries in Japan are required to operate below 10kHz by law.

### 7.4 Practical Considerations

The initial simulations presented in the previous section show that the coaxial pickup provides good coupling and output at high track currents. This section investigates design considerations such as the slot width, the copper pipe coil slot width and the spacing between toroids.

The same pickup as before (Table 3-3) was simulated, with a designed length 10 toroid pairs long. The track current and frequency remain at 100A and 38.4kHz. The pickup is simulated without spacing between toroids (previously 3mm), except when specifically noted.

#### 7.4.1 Slot Width

The main consideration is how large to make the slot in the toroid, and how it impacts the output of the pickup. The slot needs to be large enough for the track support to easily pass through it while allowing some lateral movement of the pickup. However, if it is too large, the coupling will decrease. Here the slot in the toroids (and copper pipe) is varied from 7.5mm to 11mm. As the slot size is increased, the $V_{OC}$ of the pickup drops significantly due to a lower $M$, as shown in Figure 7-7(a). The $I_{SC}$ in the pickup also decreases with larger gaps from this reduced coupling, shown in Figure 7-7(b). In order to minimise the size of the slot required, while still allowing for the track support and lateral movement of the pickup, a slot width of 9mm was chosen. This assumes a 10mm diameter track, and 3mm wide track support. This enables a lateral movement of ±6mm given the 22mm inner diameter of the toroids. The slot size can be reduced further (sacrificing lateral tolerance) provided the pickup is adequately constrained.
7.4.2 Flux Fringing

One concern with this design, which concerns all gapped inductors, is fringing flux. When a winding covers an air gap in an inductor, there will be additional eddy current loss in the coil. The copper pipe coil at the edge of the pickup will experience some eddy current loss from fringing flux (Figure 7-8), causing localised heating. To solve this, the slot in the copper pipe is designed to be slightly larger, to ensure the ends are slightly recessed from the ferrite slot. This is also desirable from a manufacturing perspective because of machining tolerances.

The design of Table 3-3 was simulated and the copper slot was varied from 9mm to 14mm. Herein, the difference between the copper slot and the ferrite slot is labelled $\delta_{Slot}$. A flux plot of the pickup showing the fringing flux in the slot is given in Figure 7-8 for two situations; with a $\delta_{Slot}$ of 0mm and 4mm. The effect on the output of the pickup is shown in Figure 7-9. The $V_{OC}$ is largely unaffected, but the $I_{SC}$ does decrease slightly with a larger slot. A 1-2mm difference should be sufficient to cover manufacturing tolerances and minimise eddy current losses from this fringing flux.
Figure 7-8: Flux plot of the coaxial pickup showing fringing flux with the copper pipe slot equal to the ferrite slot (left) and 4mm larger (right).

Figure 7-9: Simulation results of (a) $V_{OC}$ and (b) $I_{SC}$ as the slot in the copper pipe is increased.

### 7.4.3 Toroid Spacing

Another practical concern in the design of the coaxial pickup is the impact of misaligning the toroids due to either tolerance differences in the slot size, or rotational misalignment in construction. When these are stacked on the copper pipe without any spacing between them, and a misalignment exists between the slots, flux can easily cross between toroids, causing localized areas of high flux concentration which can saturate the ferrite edges and cause undue heating. To avoid this, the toroids are spaced slightly apart. The spacing between toroids should be sufficiently larger than the expected misalignment to provide a greater reluctance path for the flux. Manufacturing and construction tolerances should be within 1mm, so a spacing of 3mm or larger is desired.

To investigate the effect and size of this spacing, further simulations were carried out of the pickup described in Table 3-3 with the slot in both the ferrite and the copper fixed at 9mm. As
expected, when the air-gap between the toroids was increased, the $V_{OC}$ increases, shown in Figure 7-10(a). Normally extending the pickup length increases the $V_{OC}$ linearly. In this situation where the ferrite length is not being increased, it is close but not quite linear, due to end effect from the ferrite [16] acting as “virtual ferrite” in the gaps. There is also a slight increase in $I_{SC}$ which is shown to reach an asymptote as the length increases, (as discussed earlier in section 7.3.1).

![Graphs showing $V_{OC}$ and $I_{SC}$ vs. toroid spacing](image)

Figure 7-10: Simulation results of (a) $V_{OC}$ and (b) $I_{SC}$ as the toroid spacing is increased.

### 7.5 Constructed Prototypes

From the previous simulations, two prototypes have been constructed; a small and a full scale prototype. The small coaxial pickup prototype is used to check the feasibility of the coaxial pickup design and discover issues to do with construction. Any changes will then be applied to the full scale prototype.

#### 7.5.1 Small Scale 5kW Prototype

The small scale prototype of the coaxial pickup was designed to operate on a track with 100A track current, operating at 20kHz. This prototype is primarily for testing the coaxial pickup concept, as the size and power levels were considered more suitable for preliminary testing. The design is based on the simulation results presented in sections 7.3 and 7.4, and the full CAD drawings are provided in Appendix B.

In order to slowly ramp up the track current, initial tests were carried out using a variable frequency supply, tuned to run at 20 kHz. This power supply has no track current feedback, so the track current is adjusted by varying the input voltage with a Variac. The track was constructed of Litz wire in a plastic track support, shown in Figure 7-13, with the wires spaced 40mm apart.
7.5.1.1 Unloaded Operation

To confirm the simulations of the coaxial pickup are accurate, unloaded measurements of the pickup were taken of the test setup, shown in Figure 7-11. The pickup was tested at 20kHz, however the simulations were undertaken at 38.4kHz, thus the simulated $V_{oc}$ is reduced by the ratio of these frequencies, as shown in Figure 7-11(a). At 100A track current (the designed operating current), the $V_{oc}$ is 20.8V. This correlates with the results in Figure 7-3 for 10 toroid pairs (as constructed) when appropriately scaled for frequency. The $I_{sc}$ is unaffected by the frequency, and is 94.1A with a track current of 100A, as shown in Figure 7-11(b). These result in an $S_u$ of approximately 2kW and an average $\kappa_{\phi}$ of 0.94.

![Graphs of $V_{oc}$, $I_{sc}$, $S_u$, and $\kappa_{\phi}$](image)

**Figure 7-11:** Measured results of the unloaded small coaxial pickup; (a) $V_{oc}$, (b) $I_{sc}$, (c) $S_u$, (d) $\kappa_{\phi}$.

Due to the power limitations of the variable frequency supply used, accurate testing requires a suitably rated commercial power supply. A 10kW supply available for this has a track current of 125A RMS, and when operated at this track current the pickup has a $V_{oc}$ of 26V and an $I_{sc}$ of 118A, giving an $S_u$ of 3kVA as shown in Figure 7-11. With a Q of 2, this will
give a 6 kW prototype pickup. All the measured results correlate well with the simulated results presented earlier in the chapter.

7.5.1.2 Loaded Operation

The small coaxial pickup was tested under load on the setup described above in 7.5.1.1. The pickup was parallel tuned, and two different loads were used. The first load was a low inductance resistive load of $1\Omega$; the second was a diode load that simulates a constant voltage current sink, both shown in Figure 7-12(a) and (b) respectively. The track current was adjusted to vary the power supplied to the pickup and dissipated by the load. Figure 7-13 shows the experimental setup with the resistive load.

![Figure 7-12: Parallel tuned pickup with a (a) resistive and (b) diode load.](image)

Figure 7-14 shows the results of the highest power transferred, 1600W dissipated into the resistive load. Below, the yellow trace is the track current at 55A. The purple trace is the current delivered to the load, at 40A, and the pink trace is the voltage across the load (40V).
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Figure 7-14: Scope Capture of the small coaxial pickup delivering 1.6kW into a resistive load

Higher power delivery was limited due to a number of factors. The resistive load is thermally limited to approximately 2-2.5kW for short periods, and for this reason, a diode load was investigated as an alternative. This diode load was one previously used with IPT pickups in battery charging setups, to simulate battery banks under heavy charge. In this scenario, it acts as a current sink with a relatively constant voltage across it irrespective of the current input. In the case of the small coaxial pickup, the input was an AC input, rectified by some of the diodes in the load, with the remainder of the diodes forming the current sink. The issue here is that the diodes are not sufficiently fast enough to be operated at 20kHz effectively. Despite this, this load was run up to a power of 1.2kW, as shown in Figure 7-15, but severe harmonics in the power supply due to the presence of the diode load prevented higher power being reached. At this power level, the track current is 80A, delivering 70A to the load, with 19V across it.
Pleasingly, the pickup was found to be more than capable of supplying both loads, and the temperature of the pickup was not excessive for the power delivered. This is examined further in the following section. As mentioned above, further testing at greater power was limited by the loads available, as well as by the power supply used. This is fed from the single phase mains, which is limited to 2.4kW. With the losses of the power supply and track, this limit was approached when delivering 1600W to the pickup.

7.5.1.3 Thermal Testing

One of the key reasons for testing this small coaxial pickup under load was to see if there were any issues with the magnetic design before finalising the design of the high power prototype. Potential problems include areas of concentrated flux, or issues of inductive heating in the bus-bars. Thermal imaging is commonly used to find issues of this nature in high power systems. Thermal images of the loaded pickup are given in Figure 7-16 with the pickup operating, and Figure 7-17 showing the pickup directly after it has been removed from the track after operating for 10 minutes. The previous setup was used, with the pickup running at 1.6kW for 10 minutes on the resistive load.
Firstly, there appears to be greater heating in the centre ferrites compared with those at the ends of the receiver. This temperature difference is quantified in Figure 7-17(a), at the end of the 10 minute run under load. The centre toroids were found to operate at 54°C, approximately 1-2°C higher than the end toroids at 48.4°C as seen in Figure 7-17(c). The copper pipe conductor is at a higher temperature than these toroids surrounding it, approximately 55°C. However, as already mentioned, the toroids in the centre of the pickup are at a temperature almost identical to the copper pipe. The difference between the outer temperature of the toroids and the copper pipe is likely due to the lower thermal conductivity of the ferrite, and would equalise if the pickup ran for a longer period. However, as stated earlier, this was not possible due to the thermal constraints of the load used.

Secondly, the tuning capacitors located at the end of the capacitor bus-bar near the connection to the pickup (point A) operate at a higher temperature compared with those at the opposite end (point B), shown in Figure 7-16(a). This is due to uneven current sharing, caused by the stray inductance along the bus-bar. The higher current in the first capacitors produces extra losses. Additionally, the higher magnetic field around the bus-bar at point A where the current is higher can lead to additional eddy current heating in the capacitor foils. These are common issues with high current systems operating at this frequency, particularly in inductive heating systems. Furthermore, as the inductance of the coaxial pickup is relatively small, the stray inductance of the bus-bar is significant, and can limit the output of the pickup. The bus-bar inductance must be minimised, and is discussed further in section 7.5.2.2.
Lastly, Figure 7-17(d) focuses on the connecting end piece of the bus-bar. Initially it was suspected that this might be prone to inductive heating from the track, however from the thermal image it is clearly below the temperature of the rest of the pickup, and therefore appears sufficient for the purpose.

![Figure 7-17: Thermal Images of the Small coaxial pickup after 10 minute run time at 1.6kW](image)

As mentioned previously, testing at higher power levels is not possible due to the load used. Loads for greater power at the low voltage from the pickup, and capable of operating with 20kHz current are not presently available in the lab. 8kW resistive loads are available, but the resistance is sufficiently high that greater output voltage is required. These could however be used to load the output of a controller operating at standard industrial output.
voltages. As such, the focus shifted to the design of a suitable controller to enable further testing and operation of the full scale pickup.

7.5.2 A Full Scale 100kW Prototype

Two separate versions of the full scale 100kW pickup were constructed. The first of these consists of four 300mm sections, each with 16 pairs of toroids. Only one section was constructed, and tested under unloaded conditions. This arrangement was to be used with a regulator which includes a voltage multiplier to help raise the voltage to desired levels as discussed in section 7.6.1. However, this controller was ultimately rejected, and considered unsuitable given it is desired to utilise a Parallel Path controller as presented later in section 7.6.3. The second version of the pickup which was built had four 300mm sections connected in series. However, this pickup was reconstructed to form a single 1.2m long pickup to minimise stray inductance which was introduced due to all the unnecessary connections.

7.5.2.1 300mm Long Pickup Unloaded operation

The construction of the large coaxial pickup was based on the previous simulation results in section 7.3.2 using toroidal ferrites which became unavailable. Although toroids with similar properties and dimensions were used, in practice they were slightly shorter than the original toroids. As such, the simulated results shown in Figure 7-18 were re-simulated using the new toroid dimensions. The CAD Drawings showing actual construction are presented in Appendix C. One noted change from these drawings is that the toroid length is longer than specified in the datasheet by fractions of a mm, but the compounded length of this difference required the aluminium plate to be changed from the drawings in Appendix C.

![Graphs](image)

Figure 7-18: Unloaded measured results of a 300mm section of the large coaxial pickup; (a) $V_{oc}$, (b) $I_{sc}$. 

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The constructed pickup was again tested on a track powered using a variable frequency power supply (the setup of which was discussed previously for the small coaxial pickup). The track consisted of three turns in order to provide the larger track current up to 300A. The measured $V_{oc}$ and $I_{sc}$ are given in Figure 7-18 and compared along with the simulated results showing good correlation.

7.5.2.2 1.2m Long Pickup Construction

As previously mentioned, the 300mm long pickup section is not suitable for use with the parallel path pickup as the voltage is too low. Instead, the four sections need to be connected in series (equivalent to one large pickup) before being regulated by the controller. In fact, the pickup has been reconstructed as one large 1.2m long pickup given the existing design was difficult to series connect due to the plate connecting the two copper pipes. The pickup consists of 128 toroids on a slotted copper pipe, with a proposed output power of 100kW, a simulated $V_{oc}$ of 120V and an $I_{sc}$ of 280A on a track with 300A at 20 kHz. This gives an uncompensated power of 33.6kVA.

The new pickup has been constructed with copper pipes running the full length of the pickup (Figure 7-19), as opposed to sectioned copper pipes previously constructed, in order to minimise the leakage inductance of the pickup. Additionally, connections to the copper pipe are used on both ends for flexibility, allowing multiple pickups to easily be connected in series. One further change from the 300mm long pickup is the spacing between toroids has been slightly reduced to 2mm using foam tape for the three remaining sections (only one aluminium plate was re-machined), shown in Figure 7-19(c) and (d). This is necessary due to a small measurement error which compounds over the length of the pickup because of the number of toroids. A suitable tolerance should be included in any future revisions of the pickup.

The constructed pickup (Figure 7-20) has a measured inductance of 5.1µH at 20kHz. The AC resistance was measured at 13mΩ; however, it was found that the majority of this was due to the connection of the temporary shorting bar used for these measurements (at the far end of the pickup in the figures). This emphasises the importance of proper connections between any bus-bars, and the existing method using cap screws into threaded Tufnol will be replaced with larger bolts and captive nuts, allowing more torque to be applied and a better connection made between the bus-bars.

The leakage inductance of the pickup needs to be considered throughout the construction of the pickup, especially in the design of the bus-bars, the construction of which has not been
completed. To minimise this leakage inductance, the bus-bars will be of a planar design and insulated with thin Mylar sheet. This Mylar sheet will extend beyond the bus-bar for sufficient creepage distance for a voltage rating of at least 600V, and similar considerations will be given to the bus-bar mounting. Care has also been taken to insulate the end connections of the pickup from the aluminium mounting plate using Kapton tape, as shown in Figure 7-20(b).

![Figure 7-19: Construction of the large 1.2m coaxial pickup](image)
7.6 Proposed Control Circuits

A problem with traditional pickups in systems with large primary track currents (>150A) is that the open circuit voltage can reach levels of greater than 1kV. As such in the proposed coaxial pickup, only a single turn (copper pipe) coil is used thereby minimising the open circuit voltage, and maximising the short circuit current. However industrial pickups of this scale require output voltages of around either 300Vdc or 560Vdc. If the measured voltage is too low, it is difficult (with the proposed copper pipe) to increase the number of turns [60]. Furthermore a transformer on the secondary would add significant bulk to the pickup, not withstanding difficulties in designing an efficient high-power high-frequency transformer. As such a specialised regulation circuit is required that can efficiently switch high currents to the load.

7.6.1 Voltage Multiplier Circuit

The first option investigated was the use of a voltage multiplier circuit to boost the output voltage. Traditionally these are used for high voltage biasing with minimal current draw, as multipliers are prone to voltage sag and are unable to operate with a significant load. This is
not an issue when driven from a current source, such as a parallel tuned pickup [87]. This design utilises the new LCL topology [91, 92], which presents a unity displacement power factor to the power supply, while still acting as a current source similar to the parallel tuned pickup.

This controller is required to be used with the 300mm pickup section presented earlier in 7.5.2.1. Here the $V_{OC}$ is 25V and the $I_{SC}$ is 270A. The results from simulation of this pickup controller are shown in Figure 7-22. The output of the voltage multiplier reaches the full output voltage of 300V, and does not sag even when loaded at 900W. The output voltage ripple is due to the hysteresis of the regulator simulated, similar to that used on lower power pickups. A full wave, high current multiplier topology is used to minimise the ripple on the output, and reduce the current requirements of the capacitors. Typically, a switch after the bridge rectifier is used to decouple the pickup. With the multiplier circuit, no conventional rectifier exists, and shorting the DC output will result in shorting the output capacitance. To avoid this, switching must be done on the AC side of the pickup using an effective AC switch as shown in Figure 7-21. This requires large current switches, which are either capable of switching AC current, or with additional circuitry that force AC switching. To reduce the impact on the power supply and distribute the losses and resultant heating in the pickup, an interleaved switching scheme is intended to be used (as discussed in the following section). For this pickup, each 300mm pickup section should ideally be switched individually.

Figure 7-21: LCL tuned coaxial pickup with a 6 stage voltage multiplier; (a) high voltage configuration, (b) high current configuration.
In theory (and from the simulation presented) this pickup controller appears to solve the issue of a low output voltage, however when the losses are considered, the voltage multiplier configuration is not ideal. Each diode has a fixed forward voltage drop, $V_F$, which ranges between 1.2V – 1.8V at the power levels required. This contributes significant loss when combined with the large currents in the multiplier circuit, and the number of diodes required. Assuming diodes with a $V_F = 1.2V$, the loss for each 300mm pickup section is:

$$P_{Diode} = V_F \times I_{SC} \sum_{k=0}^{n-1} \frac{1}{2^k}$$

$$= 1.2V \times 270A \left(1 + \frac{1}{2} + \frac{1}{4}\right)$$

$$= 567W$$  \hspace{1cm} (7.1)

While this loss may be a small percentage of the overall output of each pickup section, it is still significant and the resultant heating of the pickup controller will be difficult to deal with. An alternative controller is presented later in the chapter.

### 7.6.2 Interleaved Switching Operation

One issue present when operating very large pickups on a power supply is that switching causes large load surges on that power supply, particularly with a slow switching controller. To avoid this, the proposed pickup can be paralleled to drive a single larger load (Figure 7-23), where each of the smaller section switching instants are then controlled using an interleaved switching pattern as shown in Figure 7-24. Switching these smaller 25kW
sections has less impact on the power supply, and by switching these separately in sequence, the heating throughout the pickup is distributed by simply thermal cycling between each of the switched sections. Interleaving also increases the apparent switching frequency of the pick-up, reducing the ripple of both the output and the load seen by the power supply and as lower rated semiconductors are used, the actual switching frequencies employed are faster than might have been otherwise possible. Furthermore, by combining more units in parallel, the pickup can be scaled to even larger powers.

Figure 7-23: Paralleled Pickups with a master controller for Interleaved switching.

Figure 7-24: Interleaved switching pattern.
7.6.3 Parallel Path Controller

A new controller design based on parallel AC processing units [133] may be suitable for this coaxial pickup design as discussed above. This parallel path controller is ideal due to the fact that the current supplied by the pickup can be processed in smaller lots. The primary block diagram of the parallel path controller is shown in Figure 7-25. Here, the pickup is series tuned, and forms an internal AC bus at essentially the same potential as the $V_{OC}$ of the pickup coil. Attached to this AC bus is a number of AC processing units, which feed into a DC output bus. As the pickup is series tuned and acts as a voltage source, short circuiting the Internal Bus-bar would be dangerous. However, this Bus-bar is only used internally in the pickup controller, and can be protected against short circuits using fuses.

![Figure 7-25: Block diagram of a Parallel Path pickup.](image)

Each AC processing unit consists of an LCL tuned circuit, supplying a constant current into a voltage doubler (Figure 7-26). The LCL network converts the voltage source of the AC bus into a current source at the output. This current then drives a current divider (voltage doubler) which rectifies the AC current and reduces the current magnitude. The output from all the AC processing units feed the pickup DC Bus-bar, which is the pickup output. The advantage of this configuration is that the earth is common throughout the circuit. In the case of a high power pickup, these are all identical, and the number of processing units is determined by the total required power, and the rating of each processing unit.
Figure 7-26: AC processing unit.

The LCL network is designed by calculating the impedance based on the $V_{DC}$, the desired number of networks and the desired power output. This impedance can be calculated using the following equations:

$$I_{in} = I_{L_3} = \frac{V_{out}}{X}$$  \hspace{1cm} (7.2)

$$I_{out} = I_{L_4} = \frac{V_{in}}{X}$$  \hspace{1cm} (7.3)

Where $V_{in}$ is essentially equal to the $V_{DC}$ of the pickup, and $V_{out}$ can be determined using (7.4) given the desired DC output voltage:

$$V_{out} = V_{DC} \cdot \frac{\sqrt{2}}{\pi}$$  \hspace{1cm} (7.4)

The DC output current of the AC network can be determined using the following equation:

$$I_{DC} = \frac{\sqrt{2}}{\pi} \cdot \frac{V_{in}}{X}$$  \hspace{1cm} (7.5)

To ensure continuous conduction through the voltage doubler, $L_4$ is made larger than $L_3$ by approximately 10%, and $C_3$ is added to compensate this extra inductance to give unity displacement power factor [91, 92]. The switch shown in Figure 7-26 is only a representation. Practically, this will need to be an AC switch, as it is before the voltage doubler. $C_4$ is used to maintain unity power factor when the AC processing unit is decoupled, and may be omitted in a pickup design such as this where the power rating of such components are prohibitively large.

One issue with this configuration is that the node after the second inductor, $L_4$ in the LCL network is free to have a DC bias, as there is no DC path for the current. If $C_4$ is omitted, this
is partially corrected. An alternative arrangement that improves this DC bias is with the use of a full wave voltage doubler. An AC processing unit with this voltage doubler is shown in Figure 7-27.

![Figure 7-27: AC processing unit with full wave voltage doubler.](image)

Spice simulations have been carried out on the Parallel path controller of Figure 7-27 for use on the 100kW coaxial pickup. Each AC processing unit has been rated at 5kW, for a total of 20 units. Full wave voltage multipliers are used in these units. The results of these simulations are shown in Figure 7-28. The top trace shows the current in the pickup, while the lower trace shows the power delivered by the pickup. Both the pickup current and the delivered power increase in discrete steps as each of the 20 processing units is turned on. This allows the power drawn from the power supply to be ramped up to full power in 5kW steps. As discussed earlier, this is particularly advantageous as these small load steps cause less impact on the power supply than decoupling the entire pickup in one instant.
One issue with this design is that even when a processing unit is decoupled, current continues to flow in the two inductors, with the associated losses. However, as the pickup is series tuned, a series switch in front of the LCL network can be used. Such a switch is shown in Figure 7-29. This still needs to be an AC switch, and will need a high side driver. The advantage of this configuration is that when the processing unit is decoupled, no current flows in any of the components, and the effectively isolates the unit from the AC bus.

With these two series switches, Zero Current Switching (ZCS) can be achieved even at the higher operating frequency of the IPT pickup. By using the body diodes of the switches (or added diodes) the switches do not have to be turned on at the zero crossing but can be
switched during each half cycle. However, accurate detection of the zero crossing is still required. The switching sequence is shown in Figure 7-30 with the resultant waveforms given in Figure 7-31. First, S1 turns on in the negative half cycle. As S2 is off, and D2 is reverse biased, no current will flow (Figure 7-30a). When the current becomes positive, D2 begins to conduct, at which point the AC switch is on (Figure 7-30b). During this half cycle, S2 is turned on, which has a lower voltage drop than D2, thus the current will flow through both switches (Figure 7-30c). This helps minimise losses in the AC switch, and the switches should be turned on early in the half cycle because of this. Figure 7-30(d) shows the current in the negative half cycle. This ZCS scheme is possible using natural commutation of the current. The turn off procedure for the AC switch is simply the reverse of the steps in Figure 7-30, and should be timed close to the end of the appropriate half cycle to reduce the current through the diodes below the peak load current (Figure 7-31).

Figure 7-30: Switch turn on sequence for a series switch: (a) S1 turned on, (b) current flows through S1 and D2, (c) S2 is turned on, (d) S2 and D1 conduct on the next half cycle.

The advantage of the parallel path controller is that the number of paths can be customised, and each path is designed for a lower power rating. By switching each path in steps, the impact on the power supply can be minimised. However, several additional issues need to be considered before this work can be completed, and is beyond the scope of this thesis. The first consideration is the high side driver required for the series switch. Isolated power
supplies are needed for each processing unit when series switching is used. Another issue is the leakage inductance introduced by the AC bus. Steps will be required to minimise this inductance so that all the processing units remain tuned.

**Figure 7-31: Simulated Waveforms on the AC Switch, showing:** $V_{in}$, $V_{out}$, $V_{GS}$ and $I_D$ (S1 and S2), and $I_F$ (D1 and D2).

### 7.6.4 CLC Parallel Path Controller

The parallel path controller presented in the previous section would be ideal for controlling high power pickups such as the coaxial pickup, except for two limiting factors. Firstly, the series tuned pickup acts as a voltage source during steady state, but transiently the pickup inductance is a current source. The AC switch on each path attempts to open circuit this current source, causing large voltage spikes on the AC bus. The ZCS control proposed above attempts to minimise current surges by switching when the current is zero, however at the zero crossing the $\frac{di}{dt}$ is the greatest, causing these large voltage spikes. This controller was originally tested on a pickup operating with a track current modulated at 50Hz, where the switch is operated in the nulls where the voltage and current are zero.

Secondly, the pickup adds significant inductance to the track due to the high coupling factor. As the track inductance a power supply can drive is often limited, the resulting track with the coaxial pickup in place will be significantly shorter due to this inductance, which limits the feasibility of this system for commercial applications. The series pickup in the previous section presents a unity power factor, whereas a parallel tuned pickup reflects a capacitive
reactance on the track. This reactance cancels the added inductance of the pickup, typically over-compensating it, and enables a longer track to compensate for this reflected capacitance.

A modified parallel path controller is presented in Figure 7-32 which accounts for both these issues. Firstly the pickup is parallel tuned to allow longer tracks to be used to drive the coaxial pickup. This acts as a current source at the resonant frequency. This drives a CLC impedance conversion network tuned for the track operating frequency, and acts as a voltage source feeding the Internal AC bus. Because of this and the capacitance on the internal bus, an AC switch can be used for each processing unit without the associated voltage spikes. The AC processing units discussed previously in section 7.6.3 should be suitable for use with this controller. This controller still needs to be simulated, which is beyond the scope of this thesis and is discussed further in chapter 8.

![Figure 7-32: Modified Parallel Path controller on a parallel tuned pickup with a CLC network.](image)

### 7.7 Conclusion

A number of factors present difficulties when designing high power IPT pickups. Typically, the track current must be high to achieve power transfer, but the resulting voltages within the pickup often exceed commercial safety standards. To fall within these standards, the number of turns on the pickup must be reduced, which reduces the coupling of the pickup. A coaxial pickup design as described herein eliminates this by using a copper pipe as a single turn coil, surrounded by toroidal ferrites. This maintains a very good coupling to the track, with a lower
voltage output at higher current. A slotted toroid design is used to allow rapid movement on standard tracks. However, the $V_{oc}$ of this design is very low, and new controller designs are required to give a standard industrial output voltage. Two such designs were presented in this chapter. The first uses a voltage multiplier to increase the voltage output, but was not considered suitable because of the anticipated losses. The second uses a single pickup section, but has multiple parallel paths each rated for a fraction of the overall output power. This allows good regulation of the pickup with minimal impact on the power supply. This design is presently unsuitable due to large voltage spikes from switching the pickup inductance. A modified version of this is presented to eliminate this issue and allow longer primary tracks but requires further research.
8 Conclusions and Future Work

The goal of the work carried out in this thesis was to improve high power pickups used in distributed IPT systems for two distinct applications; increasing the power delivery range of AGV pickups, and increasing the power delivery of highly constrained monorail pickups without a significant increase in size.

8.1 Quadrature Pickup

8.1.1 Quadrature Pickup

IPT pickups for AGV applications typically have limited lateral tolerance to movement across the track over which power is transferred. This is because most pickups capture the magnetic flux in a single direction, either horizontal or vertical. The Quadrature pickup described in this thesis is designed to capture both directional components of the flux, increasing the lateral range over which the pickup can operate.

Chapter 3 introduced the concept of a quadrature pickup with two initial designs, and the basic controllers required. The first of these uses two coils arranged geometrically in quadrature to capture both flux directions, while the second has horizontal split coils arranged so that the phase of the split coils determines the direction of flux captured. The geometrically quadrature pickup was chosen as the better solution as the output power profile was fairly consistent as the pickup moves across the track.

This design is based on a commercial AGV pickup, which is optimised to capture the vertical component of the flux. A horizontal coil was added to the existing ferrite structure. A particular concern is that the overall volume of the pickup necessarily increases with the addition of the horizontal coil to the pickup. In practice the clearance between the bottom of the pickup and the track is an important specification for commercial systems. Consequently, in an attempt to both limit the volume increase and maintain this clearance, the ferrite was modified resulting in a flush quadrature design with minimal impact on the output power profile.

It was noted that in order to optimise the power profile, the contribution of the two coils should be equivalent. A number of modifications to the ferrite were discussed, including the
addition of wings, extending the ends of the ferrite, and extending the centre of the ferrite. Additional wings are commonly used in commercial vertical flux pickups, but these have a more significant impact on the vertical component, whereas of particular concern here was increasing the captured horizontal component. As such, the best solution found was to extend the centre of the ferrite, provided the track conductor spacing could also be extended.

8.1.2 Tuning and Regulation

As noted the contribution of the two coils is not easily balanced with magnetic design alone and some form of electrical compensation is required. In the system investigated, the peak power of the horizontal component is not as significant and needs to be increased. This is possible by either matching the $I_{sc}$ of each of the horizontal and vertical capturing pickup coils and forcing the horizontal coil to operate with a higher $Q_V$, or by selecting a suitable number of turns to match the $V_{oc}$ of the two coils, and then to use partial series compensation to boost the current in order to match the pickup coil inductor currents. This partial series tuning boosts the current by a tuning factor called the current $Q (Q_I)$.

Chapter 4 investigates the impacts of these two different tuning methods, particularly on the impedance reflected back on to the track. When the partially series tuned horizontal pickup coil is parallel tuned, this has an increased capacitive load reflected onto the track compared with a standard parallel tuned pickup coil. In the case of the quadrature pickup, this is beneficial, as it has the effect of balancing the reflected impedance of both coils. This capacitive load (over)compensates for the added inductance of the pickup ferrite as the pickup is moved across the track. Another impact noted from the use of quadrature coils is that the flux in the pickup is increased with this partial series tuning despite operating at the same total $Q$ in the pickup circuit. Provided $Q_I$ of the receiver is designed to be below 2, this additional flux is inconsequential.

The final consideration was the overall efficiency of the quadrature pickup during operation due to lateral movement across the track. When operating near the centre of the track, the voltage of both coils resonates up. However, only the vertical coil contributes to the output when the pickup is centred here. Consequently, while the resonant current exists in the horizontal coil, it is only supplying additional losses. Likewise, when the quadrature pickup is placed directly over a track conductor, only the horizontal coil contributes to the output, and the vertical coil only adds resonant losses. To minimise these losses and improve the efficiency of the pickup to match the typical operating efficiencies achieved with a well
aligned vertical pickup, each coil was individually decoupled such that only the coil that primarily contributes to the output is allowed to operate. The exception is where both coils are required to supply the output load. A simplified version that simply decouples the horizontal coil was also investigated and is suitable if the quadrature pickup nominally operates near the centre of the track.

8.1.3 Poly-Phase and Extended Width Meander Tracks

Poly-phase and extended width meander tracks are an alternative means of increasing the lateral range over which power is delivered to a pickup receiver moving across a track. As discussed in chapters 5 and 6, these can be used in conjunction with the quadrature pickup to further increase the lateral range of a mobile receiver.

The meander track consists of a repeated single phase track, and standard pickups operating on this track still suffer from null points in the power profile. However, the quadrature pickup is ideal for this track configuration as it couples both horizontal and vertical components of flux, eliminating the null points. As noted, the spacing between track conductors is critical, and must be designed to match the pickup design otherwise the pickup output suffers and becomes uneven as the pickup moves laterally across the track.

The quadrature pickup also offers a significant advantage when used on poly-phase tracks. Due to the variation in phase between the various track conductors, a rotating magnetic field is produced around the track. As such, traditional pickups with a single coil (normally sensitive to the horizontal flux) do not suffer from null points in the power profile. However, because the quadrature pickup captures both components of flux which are now also present at all locations across the track, the resultant output is much greater and is relatively constant across the full lateral range. An advantage of the poly-phase design over the meander track is that the track spacing is not as critical. However, the output power profile is affected by the conductor spacing. Increasing this widens the track and consequently the lateral tolerance of the quadrature receiver, but also reduces the maximum power delivered.

A new track configuration was also presented in Chapter 5, termed the Double Conductor Repeated Single Phase track. This is similar to the meander track, but here each repeated cable was placed alongside and in parallel with each other, in such a manner that the track currents of these parallel cables flow in the same direction. This effectively doubles the track current in each location where it arises in order to help balance the horizontal contribution. Like the meander track, the conductor spacing is critical, however the output of a 6 wire double conductor repeated single phase track with 120mm conductor spacing closely
matches that of the three phase bipolar track with 60mm conductor spacing, whereas a meander track has a power profile where the average output is a third of the double conductor single phase track.

In order to compare all of the main track topologies suggested, an analysis was undertaken which considered the impact on the full IPT system. Chapter 6 discusses the overall track width and flexible conductor spacing of the track. Here the three phase track is preferable. However, this track requires compensation for the mutual inductance between each phase in the track, and additional tuning capacitors are required because of this mutual compensation.

However, the most important consideration is the reflected load presented to each track by the quadrature pickup. A superposition technique, presented in Chapter 5, was used to calculate the load on each conductor and hence each phase of the track. The pickup was set to deliver 2kW. The inductance of the pickup was also considered, along with both series and parallel tuning.

Because of the phase of the currents in the three phase bipolar track, the load on each phase can be either resistive, capacitive or inductive depending on the location of the pickup across the track. This reactance is independent of the tuning. The double conductor repeated single phase track does not introduce any reactance from the track phasing. Thus any reactance seen on the track is due to the reflected pickup inductance and the pickup tuning. Parallel tuning should be used, as the capacitance reflected by the tuning naturally opposes the added inductance of the pickup ferrite.

If each of the phase wires are powered by a separate inverter, the three phase track shares the load across all three inverters, whereas the double conductor repeated single phase track only shares between two adjacent phases.

However, the single phase track can be driven by either a single inverter, or multiple inverters connected in parallel. In this case, the load is equally shared across all inverters.

Overall, the new double conductor repeated single phase track presents a clear advantage over other extended track configurations. While the range is similar to that of the quadrature pickup operating on a single phase track, the output power is 5 times greater, capable of delivering 2kW with pickup offsets as large as ±100mm. On a standard single phase track, the same quadrature pickup delivers 400W over pickup offsets between ±100mm. This is a 10 times increase in range over a similar pickup that captures only the vertical flux.
8.1.4 Future Work

One of the issues with the quadrature pickup design is the inset of the horizontal coil in the flush quadrature pickup design. The recess required for the top half of the horizontal coil forms a narrow point in the ferrite where an increased flux concentration occurs. This can cause localised saturation and heating when power levels are increased. The easiest solution is only to recess the bottom half of the coil, and let the top half protrude out of the pickup, with a resulting increase in pickup volume.

An alternative solution is to shift the top half of the winding. Commercial AGV pickups typically have a 20mm wing attached to the ends of the ferrite. Shifting the top of the coil to above these wings results in the design of Figure 8-1(a). By swapping the location of the wing and the coil at the ends, shown in Figure 8-1(b), the design is similar to a new DDQ pickup recently proposed for Electric Vehicle charging [134] that also uses a split winding to capture the horizontal flux.

![Figure 8-1: Quadrature pickup with a split horizontal winding (a) on top of, and (b) below ferrite wings.](image)

Preliminary simulations of these two pickup designs have been undertaken using the parameters of Chapter 3 (Figure 3-8). The results are shown in Figure 8-2. The $V_{OC}$ is largely unchanged when the split winding is located above the ferrite wing, but when located below the wing, the $V_{OC}$ is reduced, particularly when the pickup is operating beyond 50mm from centre. The $I_{SC}$ of both pickups is improved over the standard quadrature pickup. The
pickup with the split horizontal winding on top has a reasonably consistent $I_{SC}$ over the full offset range. Significant improvements are notable between 30 – 120mm offset. The pickup with the split horizontal winding on the bottom has an increased $I_{SC}$ when operating in the centre of the track, between ±50mm.

From the resultant $S_U$ output, the first design with the winding on top appears to offer an improved output while eliminating the narrow point in the ferrite. The addition of the optional aluminium plate for shielding was also investigated but does not significantly change the results of Figure 8-2 providing the aluminium is spaced at least 3mm from the top of the pickup ferrite. This split horizontal winding design offers an improved output power profile, in addition to alleviating the issue of flux concentration in the ferrite due to the inset horizontal coil. As such, this design is to be implemented in future commercial prototypes.
Figure 8-2: Simulated results of the Quadrature pickup with wings and Double D horizontal winding showing (a) $V_{OC}$, (b) $I_{SC}$, (c) $S_U$, (d) Vertical $\kappa_\phi$, (e) Horizontal $\kappa_\phi$, (f) Total $\kappa_\phi$. 

Legend: 
- Blue: No Wing 
- Red: 20mm Wing 
- Green: DDQ Winding Top 
- Purple: DDQ Winding Bottom


8.2 Coaxial Pickup

8.2.1 Coaxial Pickup

Chapter 7 introduces a Coaxial pickup which is suited to very high power applications on monorail tracks. This pickup uses a single turn copper pipe, and maintains a high coupling with a low number of turns, enabling a high current output at voltage levels that remain within commercial standards. The magnetic design is investigated and developed in this chapter, and two conceptual controller designs are presented to boost and regulate the output voltage of the pickup to industrial levels. Brief insights into these controllers are presented, but a full investigation of these is beyond the scope of this thesis.

The slotted design presented differs from previous implementations to allow rapid movement on a monorail track without mechanical separation of the pickup when travelling over track supports. This coaxial pickup design is particularly suitable for use in clean-room or lift applications where it is constrained to a straight section of track. Past work has investigated coaxial pickup structures which are untuned and designed as a regular transformer with the output rectified and delivered to a load. Here however, the design was tuned and controlled, allowing multiple slotted coaxial pickups to operate on a single track.

The chapter presents simulated results for both a small scale and a full scale coaxial pickup. The impact of some practical issues, such as the size of the slot in both the toroidal ferrites and the copper pipe, and the space between the toroids was also investigated. Using the output of these simulations, two pickups were constructed. The smaller coaxial prototype was tested unloaded, loaded and thermally to discover any issues surrounding construction and to validate the coaxial design.

The particular issue in the design of the coaxial pickup controller is the low $V_{oc}$ due to the single turn coil. Two different controller schemes were presented for the full scale coaxial pickup to boost this voltage to standard output voltages of 330V or 560V. The first approach uses an LCL compensation network to feed a voltage multiplier. This LCL tuned pickup acts as a current source, and the voltage multiplier does not suffer voltage sag when fed with a constant current. However, the associated losses in the multiplier diodes are significant, and as such this control topology was ultimately rejected, given the difficulty to scale it for the larger design.

The second controller investigated via simulation was a parallel path controller. The pickup is series tuned, with an internal AC bus after this series capacitor. Multiple LCL networks were then connected to this bus and each used to feed a voltage doubler. Each of these paths
was individually switched, and fed into a common DC output bus. There was more than one option as to where to position the switch for each of these paths, but ultimately a series switch which completely disconnects the LCL network from the AC bus was chosen. This has the advantage of removing any loss in the LCL paths which are switched off.

Both control schemes also can use interleaved switching to minimise the power surges to the power supply, and to ensure that the losses and resultant heat are evenly distributed throughout the pickup.

### 8.2.2 Future Work

The magnetics for the coaxial pickup have been constructed, and the parallel path control circuit has been presented. In future, this controller needs to be constructed, and the pickup needs to be fully tested under load. A particular issue is that the coaxial pickup adds significant inductance to the track due to the high coupling factor. The track inductance a power supply can drive is often limited, and the resulting track with the coaxial pickup will be significantly shorter because of the extra inductance. As such, this coaxial design should be parallel tuned, as the capacitive reactance cancels the added inductance of the pickup, typically over-compensating it and this enables a longer track to compensate for the extra capacitance reflected on the track.

A modified parallel path controller is proposed in chapter 7. This design uses parallel tuning with the advantages already stated above. This acts as a current source, supplying a CLC impedance conversion network, the output of which acts as a voltage source, and connects to an internal AC bus. The parallel processing units connect to this bus, and output to a common DC output. Unlike the previous parallel path design, series AC switches can be used for each processing unit as the inductors have a current path through the capacitors in the CLC network when each path is decoupled. This controller requires a thorough analysis, which is beyond the scope of this thesis.
Appendix A. **Reflected Impedance Proof**

From (4.7):

\[ Z_r = \frac{\omega^2 M^2}{\left(\frac{\omega L_2^2}{\omega C_{L2}} - 1\right)^2 \left( R - j\omega L_2 + \frac{j}{\omega C_{L2}} \right)} \]  

(9.1)

Considering only the reactive component:

\[ X_r = \frac{-\omega^2 M^2}{\left(\frac{\omega L_2^2}{\omega C_{L2}} - 1\right)^2} \]

(9.2)

\[ = -\omega M^2 \frac{\omega^2 C_{L2}}{\omega^2 L_2 C_{L2} - 1} \]

Where:

\[ Q_l = \frac{\omega^2 L_2 C_{L2}}{\omega^2 L_2 C_{L2} - 1} \]

(9.3)

Substituting (9.3) into (9.2) results in:

\[ X_r = \frac{-\omega M^2}{L_2} \cdot Q_l \]

(9.4)

and

\[ S_u = \frac{M^2}{L_2} \omega I_1^2 \]

(9.5)

resulting in:

\[ X_r = \frac{Q_l S_u}{I_1^2} \]

(9.6)
Appendix B. CAD Drawings of the Small Coaxial Prototype Pickup

The CAD drawings presented here match the constructed small coaxial prototype pickup. No changes were made during construction of the pickup.
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<td>1</td>
<td>ALUMINIUM MOUNTING PLATE</td>
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<td>SUPPORT SHAFT – 360MM LONG 6MM DIA.</td>
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<td>M3 X 10 HEX SOCKET CAP SCREW</td>
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Toroid from Cosmo Ferrites
Material: CF195
Permeability: 5000 ± 20%
Material: TUFNOL – Cotton Grade

Thicknes: 3mm

\[ \phi 6 \]

\[ \phi 22 \]

\[ \phi 36 \]
Material: Aluminium

Scale 1:1

Dimensions:
- Length: 360
- Width: 90
- Height: 45
- Diameter: Ø6
- Hole: M4 x 5, Ø3.3
- Edge: R1, 2
- Gap: 3, 8
- Slot: 7.5

Title: Aluminium Heatsink Plate

Drawing Number: 10kW Pickup
Material: Nickel Plated Copper

Dimensions:
- 36
- 22
- 20
- 10
- 40
- 350

Copper Pipe Coil
Material: TUFNOL – Cotton Grade
Material: Nickel plated copper
Appendix C. **CAD Drawings of the Large Coaxial Prototype Pickup**

The CAD drawings presented here represent the initial version of the large coaxial prototype pickup, consisting of four 300mm long sections. However, the final constructed prototype varies from these drawings, as a longer 1.2m long pickup was required. Additionally, a small dimensional error of the toroids used compounded, and modifications were required to allow for this error. The changes are listed below:

- Slotted copper pipe increased to 1.2m length and end connecting plate removed.
- Bus-bar end connections on both ends of the slotted copper pipe.
- One aluminium plate re-machined with an increased space between slots to allow for the error in the toroid length.
- Remaining three aluminium plates were not re-machined. Double sided foam tape was used instead of the untabbed spacers to allow for the slight increase in length of the toroids.
- Kapton tape applied to the ends of the aluminium plates to provide insulation from the bus-bar end connections.

Photos of the final constructed pickup with these changes are shown in Chapter 7.
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<td>SUPPORT SHAFT – 295MM LONG 6MM DIA.</td>
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<td>6</td>
<td>M3 X 10 HEX SOCKET CAP SCREW</td>
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</tbody>
</table>
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Material: TUFNOL — Cotton Grade
Material: Nickel plated copper
Material: TUFNOL – Cotton Grade

Thickness: 3mm

Tabbed Spacer

PROJECT NUMBER: 100KW Pickup
DRAWING NUMBER:
Material: TUFNOL – Cotton Grade

Thickness: 3mm

ø84

ø54

R5

26

12.5

R1

100

 Spacer
Toroid Ferrite from High Permeability Ferrite Cores Series Products
Marque Magnetics Product No: MMQ-00398
H85.7 x 55.5 x 12.7 – R7K – C
AL (nH/N≈2) <\(>\) 25% = 7716
References


