Finite Element Assisted Study of Magnetic Configurations of Flat Pickups for Inductively Coupled Power Transfer Systems

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Abstract**—**This publication describes the findings from a finite-element assisted study of an Inductively Coupled Power Transfer (ICPT) system with flat pickups. Results from the analysis of pickup elements are presented in a graphical form allowing comparison with a conventional ('original') pickup. The pickups were examined in unipolar and bipolar ICPT systems. Unlike the existing pickup, the proposed configurations utilize two components of the magnetic flux density, and are characterized by high-power transfer ability as well as much better response to the misalignment problem. Some recommendations and possible means for further improvements for higher power efficiency are also put forward.

Index Terms**— Inductive Power Transfer, Flat Pickup, Magnetic Field Components.**

I. Introduction

FLAT pickups are commonly used in under-floor Inductively Coupled Power Transfer (ICPT) systems in applications where no mechanical contact is essential or beneficial [1] – [8]. Such systems are commonly used in all range of power supply devices for clean rooms, battery charging modules, monorail transportation, and biomedical apparatus. ICPT systems are very popular and readily applied in production and fabrication lines to power moving platforms as shown in the example in Fig. 1.

Considering the principle of its operation, an ICPT system can be regarded simply as a transformer, where the energy is transmitted via the alternating magnetic field. The ICPT is composed of a primary circuit installed in the floor (ground) close to the floor surface and a so called *flat pickup* installed under the vehicle chassis [9] – [11]. While the position of the primary circuit remains unchanged, the flat pickups travel with the vehicle. It is common practice to have one primary circuit delivering power to several pickups simultaneously.

The primary circuit in under-floor applications may appear in two different configurations. The first one is called the *closed loop*, where pickups are subjected to the magnetic field produced by the electrical current flowing in one direction only. This configuration is often referred to as the *unipolar configuration*. The second configuration of the primary circuit is called the *bipolar configuration*, and is achieved by placing pickups close to a wire-track in which two electrical currents flow in opposite direction. In this publication the performance of the analysed flat pickups is assessed for both unipolar and bipolar configurations.

Fig. 2 shows the diagram of an ICPT system with a linear track. Due to the unique application and space constrains the pickups must be relatively thin so they can be installed under the platform without touching the ground. A resulting small distance from the floor ensures higher power transferred by the pickups.

A typical geometry of a conventional flat pickup is depicted in Fig 3. This 'existing' pickup is mainly designed to work in unipolar configurations, where it collects the power utilising only one component of the magnetic flux density produced by the primary circuit, namely the tangential component along the *x*-axis direction.

The paper begins with a description of the magnetic constrains affecting the pickup's power transfer efficiency, pointing to the so called 'inter conductor cancellation factor' and its role in power transfer process. In the next section the results from the Finite Element Method (FEM) study of three new flat pickup configurations are presented. Additional recommendation and modifications are then suggested finishing with brief but practical conclusions.

Fig. 1. A photograph of an ICPT moving platform applied in a vehicle fabrication line.

Manuscript received June 30, 2006.
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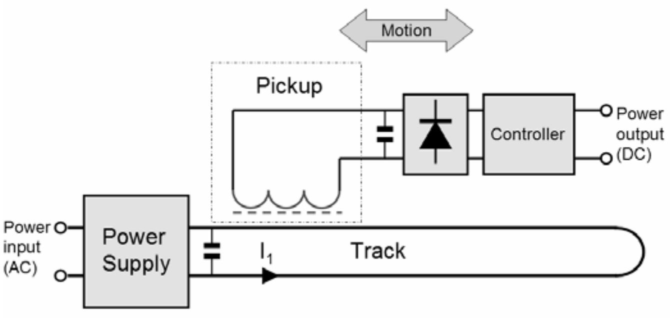

Fig. 2. A diagram of an inductively coupled power transfer system. Only one pickup is shown but in practice several pickups can be accommodated.

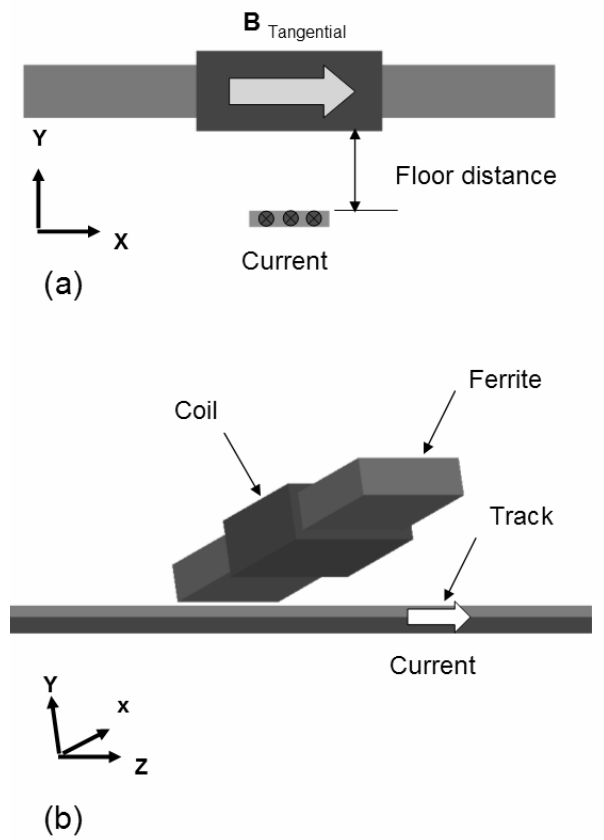

Fig. 3. A conventional flat pickup in unipolar configuration: (a) 2D view, (b) 3D view. Images obtained from FEM software JMAG Studio.

II. Magnetic Constrains to Power transfer

The nominal power output of an un-tuned pickup (S_u) is given by the product of the secondary coil's open circuit voltage and short circuit current [12], [13] as:

$$S_u = \omega M I_1 \cdot \frac{M}{L_2} I_1 = \omega M \frac{N_1}{N_2} \kappa I_1^2 \qquad (1)$$

where: ω is the frequency of the track current,
M is the mutual coupling between L_2 and the track,
N_2 is the number of turns of the pick-up coil.

Equation (1) is a well know form of the pickup's power expression. It points to the most significant magnetic factor affecting the power, which is the mutual flux that links the primary circuit and the pickup coil, and the coupling factor [13] is given by

$$\kappa = \frac{\Phi_M}{\Phi_{L2}} \qquad (2)$$

where Φ_M is the mutual flux linking flat pickup and the primary circuit, Φ_{L2} is the total flux in pickup coil and *L2* is the inductance of the pickup.

Unlike the closed loop (unipolar) ICPT systems, in which the magnetic field interfering with the pickup is produced by one primary current only, the linear track systems are also affected by the *inter conductor cancellation factor* (*ICCF*) [13]. The power of such systems can be described as

$$S_u = \frac{\omega \kappa^2 (1 - ICCF)}{\Re} \qquad (3)$$

where $\Re$ is the reluctance of the total flux, κ is the magnetic coupling factor and *ICCF* is the already mentioned inter conductor cancellation factor.

Figure 4 shows the formation of the *ICCF*. The inter conductor flux caused by the common mode effect is cancelled if both currents I_{1A} and I_{1B} are applied. The *ICCF* is a serious problem and in extreme cases may reduce the power of the pickups by as much as 50% [6].

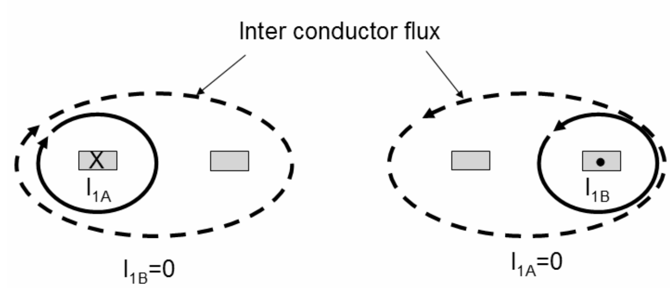

Fig. 4. Formation of the inter conductor cancellation factor *ICCF*.

When using finite element analysis the power of the ICPT systems may be obtained from two relatively simple analyses. The first one aims at finding the open circuit voltage V_{OC}, whereas the second determines the short circuit current I_{SC}. The uncompensated power can then be calculated as

$$S_u = V_{OC} I_{SC} \qquad (4)$$

where V_{oc} is the open circuit voltage and I_{sc} is the short circuit current of the pickup coil [10].

Although the above technique of calculating power from two simple numerical models is quick and reliable, the procedure does not reveal any factors or parameters which could be observed to assist the pickup's design process. Thus, in order to design a well performing pickup, first of all the magnetic constrains must be considered.

III. ANALYSED PICKUP CONFIGURATIONS

The power collected by a conventional pickup depends strongly on its position with respect to the primary circuit. In a unipolar configuration, in the case when the pickup is located directly above the track (perfect alignment), the system transfers maximum power. However, this is not the case in the bipolar configuration where the perfect alignment position yields zero power. During normal operation the pickups are continuously affected by misalignment problems as moving platforms turn around the corners. This results in inevitable loss of efficiency and reduced power transfer.

In the search for improved performance, for the purpose of this study, three new models of flat pickups have been considered, *Model 1*, *Model 2*, and *Model 3* as shown in Fig. 5, Fig. 6 and Fig. 7 respectively. Unlike the original flat pickup shown in Fig. 3, the proposed flat pickups are designed to utilize two components of the magnetic flux density, $\boldsymbol{B}_{\text{tangential}}$ and $\boldsymbol{B}_{\text{normal}}$. The main motivation behind introducing the two-component configuration is an attempt to design a flat pickup which has better response to the misalignment problem. The second objective is to reduce the 'power to volume of ferrite ratio', which in practice means delivering maximum power from a minimum volume of the pickup's ferromagnetic core.

As two components of the magnetic flux density are to be utilized, the proposed models of flat pickups require at least two coils. *Model 1* actually consists of three coils as shown in Fig. 5. *Model 2* has a similar configuration, but its behaviour in a bipolar ICPT system is different to *Model 1*, which is described later in the text. *Model 3* uses very little of ferrite and is composed of two coils crossing each other, designed to collect power from two components of the magnetic field.

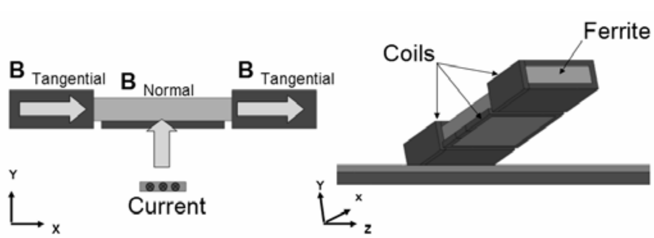

Fig. 5. Proposed "Model 1" configuration utilizing two components of the magnetic flux density.

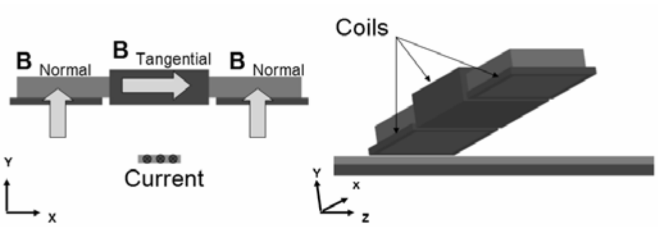

Fig. 6. Proposed "Model 2" configuration utilizing two components of the magnetic flux density.

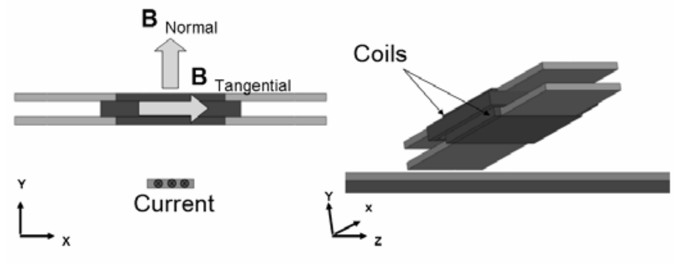

Fig. 7. Proposed "Model 3" consisting of two coils crossing each other utilizing two components of the magnetic flux density.

As the main goal is to determine the pickup's response to the misalignment problem, the proposed models were analysed in both unipolar and bipolar configurations. The pickups were moved from their central position along the *x*-axis direction and the total uncompensated power was calculated. It has been assumed that all coils are independently tuned, and are not electrically connected; thus the total power of the pickup system may be expresses as a sum of the power delivered by each component coil.

Figure 8 shows variation of the resultant power as a function of the distance from the central position for a unipolar configuration in which the value of the primary current was assumed as I_1=80A at 10kHz and with N=3 turns. The 3D area in which all pickups are enclosed was 100×35×12.5mm, and distance to the floor 15mm (Fig. 1). The power variation chart shows that all proposed models perform better then the conventional design providing higher power outputs. The pickup called *Model 1* shows some interesting features. In this case, although the power transferred in the perfectly aligned position is less then in a conventional pickup, the overall power profile is better and not so strongly affected by the misalignment problem. Even when the pickup is completely off the track, it still delivers about 25% of its maximum power, compared to 8% in the case of the 'original' design, which appears to be quite a significant improvement. Figure 9 illustrates a graphical representation of the misalignment problem in unipolar and bipolar arrangements.

Figure 10 shows the power variation from the analysed pickups placed in bipolar configuration; once again, *Model 1* shows a very impressive profile. Unlike the other models delivering zero power (or close to zero) in the central position, the *Model 1* pickup transfers quite a large amount of power in the central position as well as in misaligned positions.

The other analysed models have different advantages. The pickup called *Model 2* transfers far more power than all other analysed pickups. It would therefore be recommended in applications where high power is a priority. The third pickup (*Model 3*) uses a very small volume of the ferromagnetic core, thus being light and relatively inexpensive. It could find applications in powering small objects such as toys, sensors, medical and monitoring equipment.

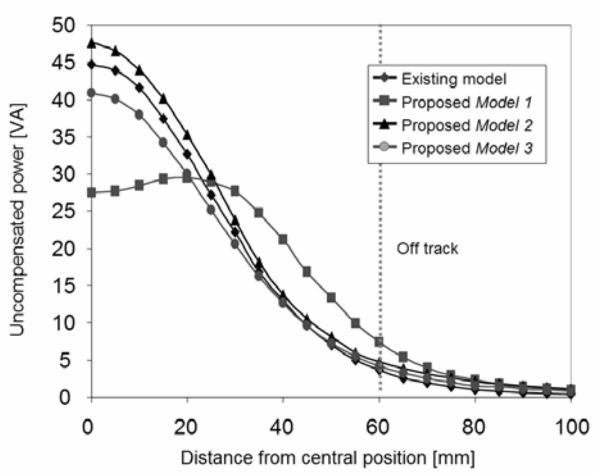

Fig. 8. Analysed pickups under closed loop (unipolar) excitation.

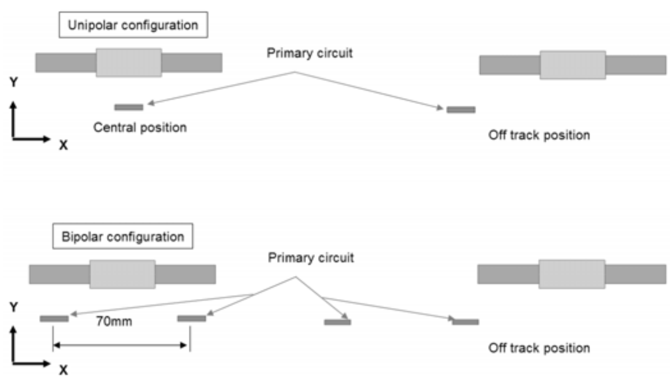

Fig. 9. Graphical depiction of the misalignment problem in unipolar and bipolar configurations.

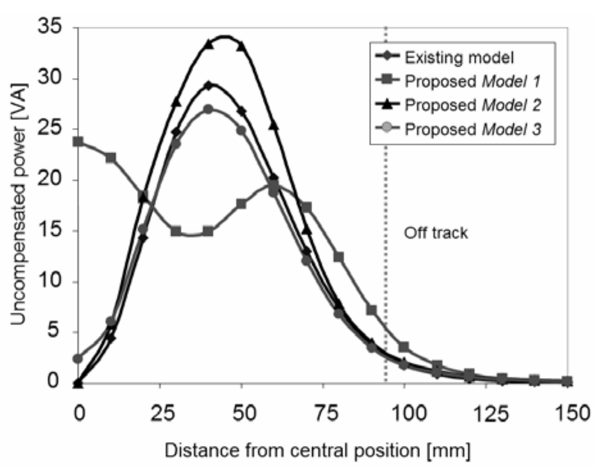

Fig. 10. Analysed pickups on linear track excitation. I_1=2×80A at 10kHz, and N=3 turns.

IV. Recommended Flat Pickup Configuration

The excellent performance of the *Model 1* pickup makes it suitable for applications where a vehicle (or a moving platform) is subjected to large misalignment problems. It behaves well in both unipolar and bipolar configurations. However, in the bipolar configuration, the pickup (as well as the other pickups) show an overall power drop. The average power delivered by each pickup is lower in the bipolar configuration, even though – compared to the unipolar configuration – the bipolar track is supplied by double the current I_1=2×80A. This is caused by a relatively large inter conductor cancellation factor ICCF (3), and small magnetic coupling κ. In order to increase the overall power in the bipolar ICPT system, the proposed *Model 1* pickup has been modified, and two "wings" added as indicated in Fig. 11. Unfortunately, this may result in the need to redesign the chassis of the vehicle (or moving platform) to accommodate these extra pieces of ferrite. The greater height of the wings, the more power is transferred by the pickups. Figure 12 illustrates the power increase due to the height of the wings.

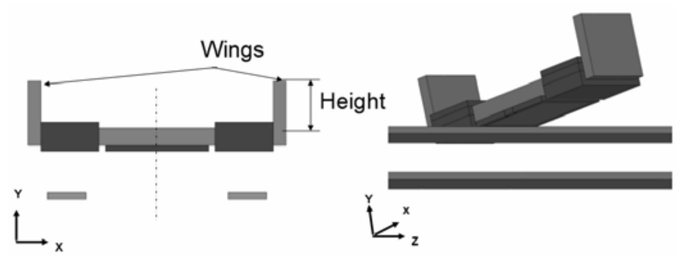

Fig. 11. Ferromagnetic wings added to the core to improve the power transferred by the *Model 1* type pickup.

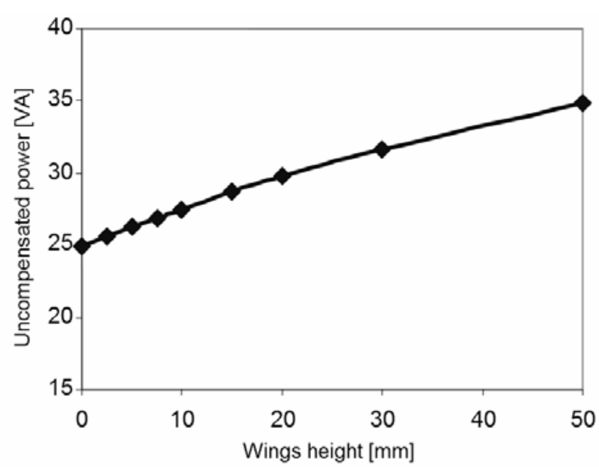

Fig. 12. Power increase in *Model 1* pickup in the bipolar ICPT system caused by ferromagnetic wings added to each site of the pickup's core.

The entire pickup with the 15mm-high wings has been analysed in the bipolar ICPT configuration to check its response to the misalignment problem. The resultant chart is presented in Fig. 13 and shows that, amazingly, the pickup with wings appears to perform better in each possible position with respect to the track. In the central position (distance 0mm) the power has increased significantly, satisfying the criteria for high power transfer in the "on track" situation. Moreover, the power in the "off track" position has also been increased. The added wings could in fact be made even higher to have more impact on the power distribution profile; however, some construction as well as economical constrains must be considered for each application.

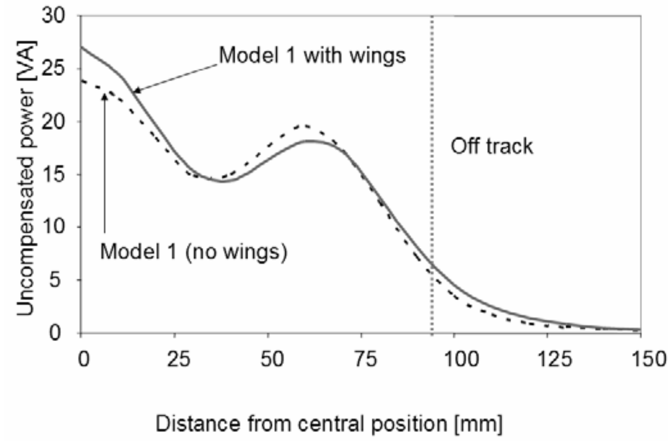

Fig. 13. Power profile of *Model 1* type pickups with 15 mm ferromagnetic wings placed as shown in Fig. 11 compared to the results obtained from *Model 1* without any wings.

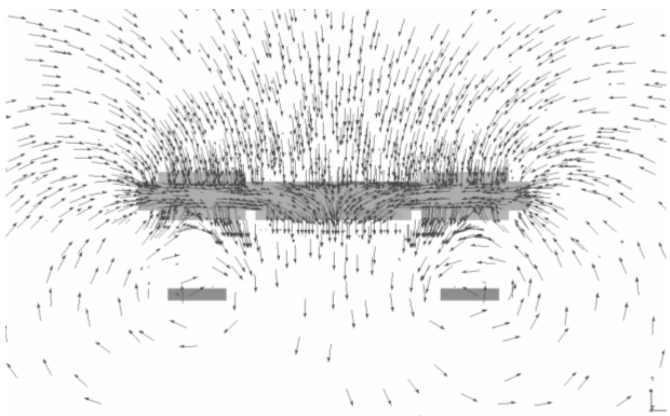

Fig. 14. Magnetic field vectors of *Model 1* in bipolar configuration.

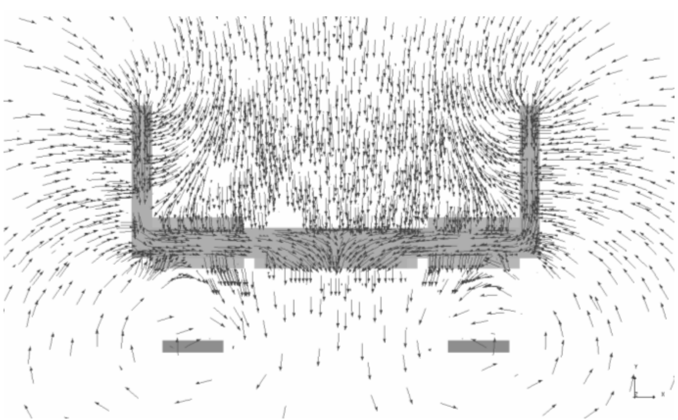

Fig. 15. Magnetic field vectors of *Model 1 with wings* in bipolar configuration.

The role of the wings is relatively simple to explain. These extra pieces of ferrite not only reduce the ICCF, but also capture some portion of the magnetic flux and redirect it into the coils located on each side of the pickup. This phenomenon can easily be observed in Fig. 14 and Fig. 15. The figures show comparable 2D images of the magnetic flux density vectors obtained for the *Model 1* configuration without and with the wings respectively.

V. Conclusions

The paper has demonstrated the usefulness of finite-element assisted analysis of magnetic field distributions in the design of new configurations of pickups for Inductively Coupled Power Transfer (ICPT) systems. Significant improvements of performance have been made possible by using modern field simulation software. It has been shown that particular attention needs to be paid to the field cancellation phenomenon. The field analysis undertaken facilitates understanding of the performance and aids the optimisation process.

Three novel pickup configurations have been introduced and analysed in detail. The proposed pickups, although probably more expensive to build, can be characterized by higher power transfer ability and may therefore be particularly applicable in high power applications. They also offer a better power profile under misalignment (off-track) position, a condition of special concern in practical applications.

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