Magnetic Interference in Multi-Pickup Monorail Inductively Coupled Power Transfer Systems

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This paper examines magnetic interference in a selection of differently shaped ICPT pickups. Two distinct trends in the results of Finite Element Method analysis were observed as the magnetic interference had either a positive or negative effect on the total power output. The paper presents a new shape of pickup with high power output that takes advantage of the positive proximity effect. Also presented are results of the study and power to volume ratios which are one of the metrics used in the design process.

Key Words: Inductive power transfer, Electromagnetic induction, Asymmetrical pickups, FEM modelling.

1. Introduction

Inductively coupled power transfer systems are used extensively in low and high power applications where mechanical isolation between the power source and receiver is required. A common utilisation of ICPT technology in clean rooms or automotive production lines is to supply power through a monorail track to a moving platform [1]. An example of factory automation using this technology is provided in Fig. 1.

In the bipolar monorail, current is passed through two stationary tracks as shown in Fig. 2a and Fig. 2b. A coil wound on a permeable core is placed near the track without touching it. This 'pickup' captures a portion of the magnetic flux from the track, and after rectification by power electronics circuitry the power is available for use on the moving platform [2].

The E shaped pickup is the most common design due to its simplicity, however many shapes are now in development that can provide much more power for the same volume of core material [3], [4].

In order to increase the power available to a moving platform, pickups can be placed alongside one another to form a multiple pickup system. It has been observed that these systems are affected by a mutual coupling between the pickups that has been described as the proximity effect [5].

The proximity effect between systems of E and Z shaped pickups has been presented previously [5], here a further analysis will be presented that will expand the focus to many other possible shapes for the bipolar monorail.

The paper begins with magnetic design considerations, including the proximity effect and the useful power to volume ratio (S/v_{core} ratio). The following section will present results from a Finite Element Method (FEM) analysis of the proximity effect in a range of differently shaped pickup systems, and a new shape of pickup which takes advantage of the 'positive proximity effect' is presented. The final section provides some brief conclusions.

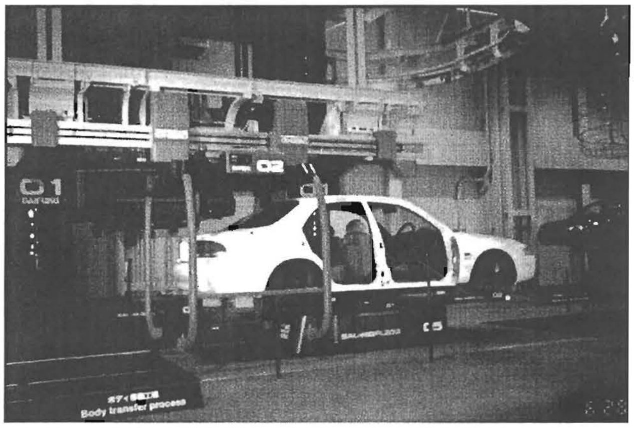

Fig. 1. ICPT as applied to automotive manufacturing

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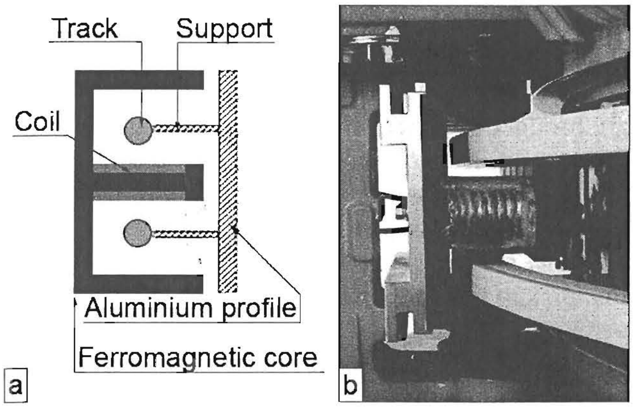

Fig. 2. E-pickup on bipolar monorail track (a) Cross section (b) ICPT application, E pickup with central coil attached to moving platform

2. Magnetic Design Considerations

A schematic representation of the ICPT system is given in Fig. 3. The uncompensated power of each un-tuned pickup is given by:

$$S_u = V_{oc} I_{sc} = \omega M I_1 \cdot \frac{M}{L_2} I_1 \qquad (1)$$

Where V_{OC} and I_{SC} are the open circuit voltage and short circuit current of the pickup L_2, ω is the frequency of the track current I_1, M is the mutual coupling between L_2 and the track [4].

When more than one pickup is used in an ICPT system, there is a nonlinear increase in power. This is dependant on the distance between the pickups, and is explained by a mutual inductance existing between the pickups [5]. This proximity effect has been defined by conducting FEM analysis on a system of two pickups as illustrated in Fig. 4. The magnetic effect of the track current is removed by setting that current to zero. One of the pickups is excited with a small AC current. The flux emitted by this pickup Φ_E, the mutual portion of that flux which penetrates the receiving pickup $\Phi_{M\text{-}PE}$, and the flux in the receiving pickup Φ_R are measured. The proximity effect is then calculated as:

$$PE = \frac{\Phi_R}{\Phi_E} \times 100\% \qquad (3)$$

In this case $\Phi_R = \Phi_{M\text{-}PE}$, but as further pickups are added to the system this may not be the case.

The uncompensated power to volume ratio (S/v_{core} ratio) is a useful design metric when comparing the effective use of permeable core material, and is measured in mVA/mm^3.

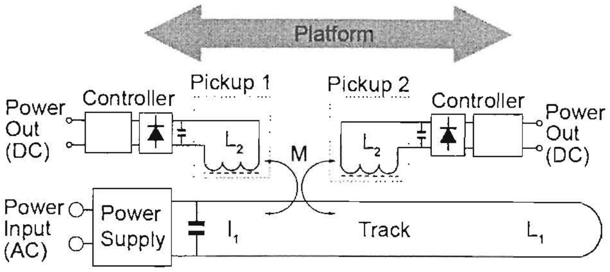

Fig. 3. Schematic representation of ICPT system

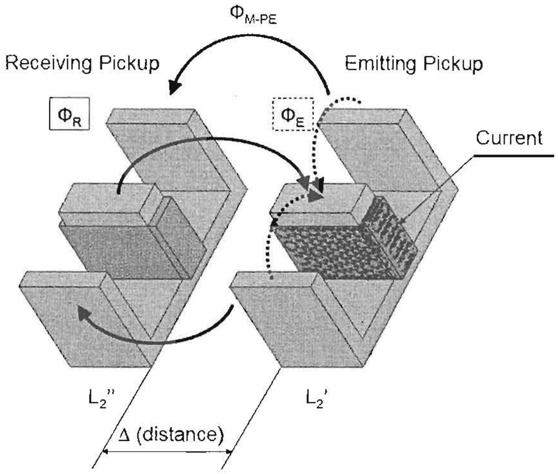

Fig. 4. The proximity effect is defined by removing track currents [4]

JMAG Studio software allows the creation of an electronic circuit external to the magnetic model, in which a FEM coil can be connected with other standard circuit components. Each pickup coil in the magnetic model is labeled with the appropriate settings, and in this case the external circuit contains a single pole switch connected across the coil (Fig. 5).

The no-load or open circuit voltage (VOC), and short circuit current (ISC) values can be substituted into (1) to find the uncompensated power.

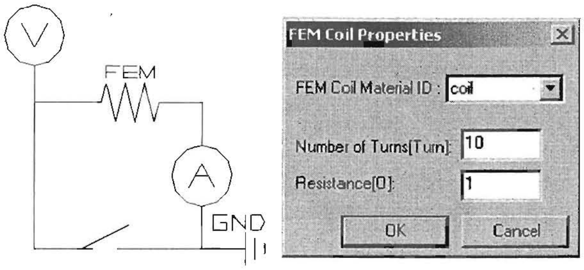

Fig. 5. Simple electronic circuit for calculating uncompensated power of ICPT pickup using FEM (JMAG Studio v8.1, The Japan Research Institute Ltd)

3. FEM Analysis

To measure the effect of the magnetic interference on power output, a FEM model was created that contained a bipolar monorail with two pickups separated from each other by a distance Δl (Fig. 6).

In order that the different ferrite shapes could be compared to each other, a 'figure 8' pickup model was created, and elements of this were removed as necessary to create the other shapes. Fig. 7 contains the dimensions of the figure 8 pickup, while Fig. 8 contains a cross sectional representation of the other shapes considered in the study.

The monorail track was supplied with a 10kHz, 80A alternating current. A ferrite material equivalent to NKK 50EF1000 electrical steel was simulated.

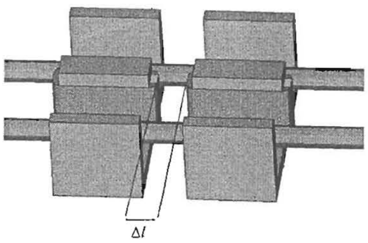

Fig. 6. Two pickups separated by distance Δl

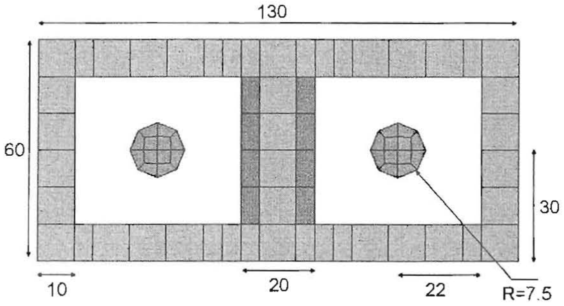

Fig. 7. Dimensions of figure 8 pickup (mm)
Depth is 60 mm

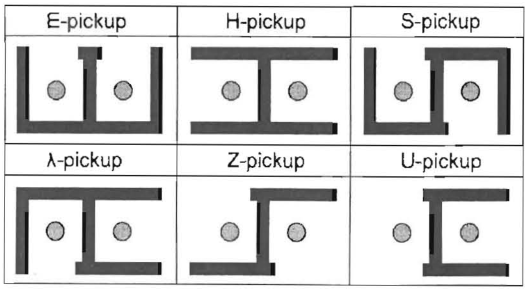

Fig. 8. All shapes considered in study

3.1 Results

The separation distance Δl between two identical pickups was varied between 1mm and 100mm, and uncompensated power calculated as in (1). Fig. 9 shows the results for these models.

The overall system power declines as the pickups are brought together, irrespective of the shape of the ferrite core. It has been suggested that this proximity effect could be used to an advantage in pickup design [4]. If the second Z-pickup is positioned in an alternate configuration for instance, the flux leaving this pickup can feed in phase to the first pickup as is shown in Fig. 10. This concept is now extended to the other shapes presented in Fig. 8. In some of these configurations, the track supports would need to be modified or removed altogether. This could be an acceptable solution in an application where the track was rigid or suspended in a vertical orientation.

Further analyses were conducted on the alternately configured pickups pictured in Fig. 11. The resulting power versus Δl results are displayed in Fig. 12.

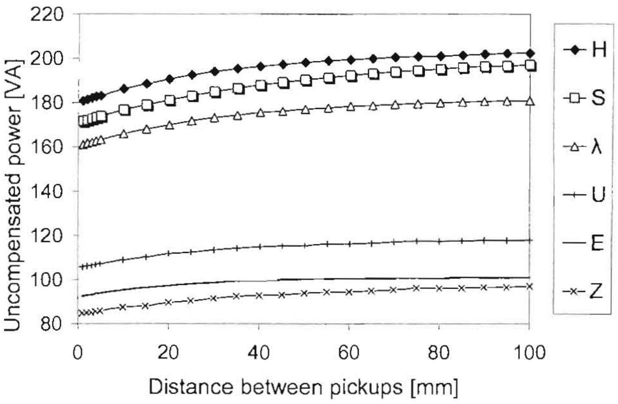

Fig. 9. Uncompensated power vs. separation distance – regular configuration

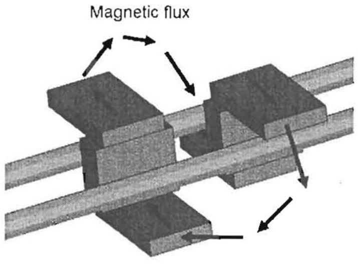

Fig. 10. Flux path between alternately directed Z pickups. [4]

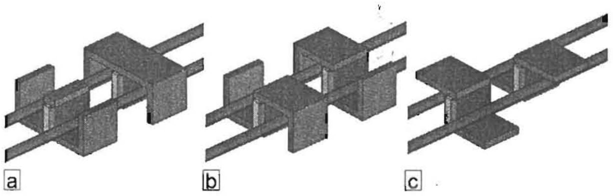

Fig. 11. Alternately configured pickups.
(a) E-pickups. (b) S-pickups. (c) Z-pickups.

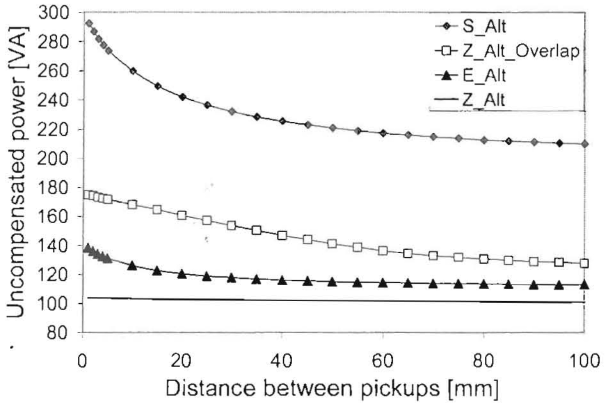

Fig. 12. Uncompensated power vs. separation distance – alternate configuration

The alternate S and alternate Z-pickups both have useful characteristics, the S with greater overall power and the Z with a more widely applicable track support configuration. The alternately configured pickups have greater power output at 1mm due to the constructive interference of flux flowing in the proximity region between the pickups as shown in Fig. 10. The magnetic flux emitted from the regularly configured pickups cancels out in this proximity region, reducing the total flux coupled by the coils on each pickup.

3.2 Development of improved pickup

The alternate Z with overlapping foot pickup shown in Fig. 13 was created to provide a larger platform for the proximity flux to launch from as it flows between the two alternately positioned pickups. Power versus separation distance results are included in Fig. 12.

This pickup system has the highest power to volume ratio of all the systems analysed for the current paper, as is shown in Fig. 14. Two H-pickups have a comparable power output, however the clear advantage over two H-pickups is that less ferrite is used resulting in a lighter system.

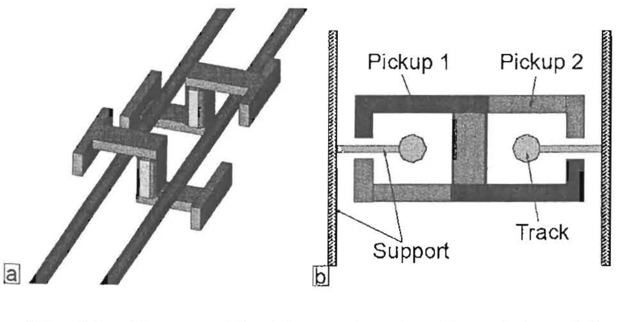

Fig. 13. Alternate Z with overlapping foot pickup (a) oblique view (b) cross section showing track and supports.

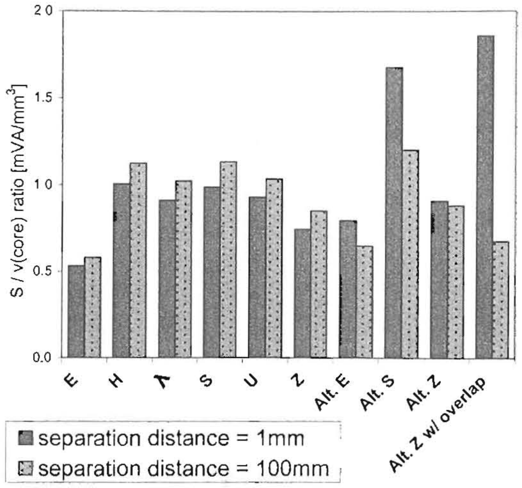

Fig. 14. Power to volume ratios are a measure of a pickup's efficiency

4. Conclusion

Efficient use of ferrite is important to the improvement and development of ICPT systems. Utilisation of the proximity effect has lead to the design of more effective pickup cores, and further research will hope to find ways to implement these in industrial applications.

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