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# Magnetic design considerations to improve nonlinear characteristics of inductively coupled power transfer systems

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## Abstract

**Purpose** – This study seeks to apply finite element analysis to study the proximity effect in a multi-pickup inductively coupled power transfer system, quantify the effect and propose improved pick-up configurations.

**Design/methodology/approach** – A mixture of approximate analytical formulae and accurate finite-element simulations has been used as a tool for qualitative and quantitative analysis. Simplified consideration of magnetic flux paths aids understanding, whereas detailed numerical computation provides reliable performance prediction.

**Findings** – It is shown that a multi-pickup formation of conventional E-pickups may lead to power loss due to negative coupling between neighbouring pickups and that the phenomenon is nonlinear. Thus, two novel configurations for multi-pickup systems have been proposed, an alternately-directed Z-pickup and a spilt-type E-pickup, both showing improved linearity, increased total power and more efficient use of ferromagnetic material.

**Research limitations/implications** – The investigation aimed mainly at the electromagnetic performance, while economic issues will still need to be addressed.

**Practical implications** – The proposed pick-up configurations may be very helpful in systems where improved performance is needed but space or configuration limitations restrict or eliminate the possibility of using other designs.

**Originality/value** – The finite-element aided magnetic field simulation has proved invaluable in achieving difficult design objectives. The combination of a simplified analytical approach and detailed numerical analysis has provided a reliable tool for accomplishing improved designs.

**Keywords** Inductively coupled power transfer systems, Finite element analysis, Design methods

**Paper type** Research paper

## 1. Introduction

The inductively coupled power transfer (ICPT) technology has made significant advances in applications where no mechanical contact is essential or advantageous. Nowadays ICPT systems are widely used in low- and high-power applications in both domestic and industrial markets (Klontz *et al.*, 1991). A popular function of the ICPT technology is to power monorail transportation systems used in clean rooms or automotive production lines.

A diagram of a typical ICTP system is shown in Figure 1; it comprises a current carrying Litz-wired track and a pickup (Green and Boys, 1994). The pickup is attached

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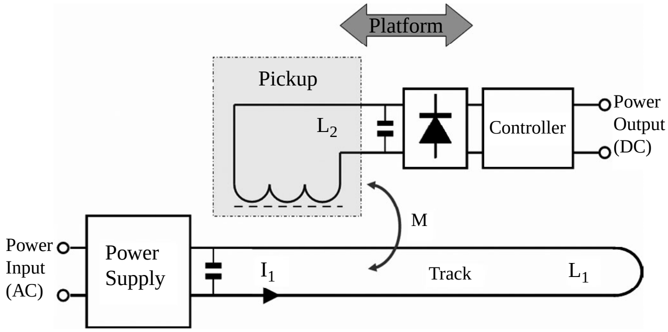


**Figure 1.**
Diagram of an ICPT system

to a moving platform and is designed to travel along the primary track. Standard monorail ICPT systems are often based on an E-pickup, named after the shape of the ferromagnetic core. Figure 2 shows an example E-pickup in a monorail ICPT system. Although the E-pickup configuration is very popular, it has only one major advantage that the e-shaped coil/core assembly can be easily installed into the ICPT track by simply approaching the track conductors from one side. The disadvantages of the E-pickup, on the other hand, are numerous. In particular, the E-pickup has an inefficient magnetic design resulting in a rather low power to volume of ferrite ratio (S/v) (Kacprzak, 2006a, b). Hence, when high-power transfer is required, the monorail platform often uses two E-pickups to increase the power. However, a multi-pickup formation of E-pickups produces the so-called negative mutual coupling between neighbouring pickups, resulting in a nonlinear reduction of power influenced by the distance between adjoining pickups.

The purpose of this publication is to flag the nonlinear power drop problem and explain its origin. Improved pickup arrangements are also suggested which reduce this nonlinear phenomenon and increase the overall power and the effective use of ferrite material.

## 2. Determination of power transferred by the E-pickup

In order to predict computationally the power transferred by the pickup, two separate finite element method (FEM) analyses are usually performed. The first calculation aims at finding the open circuit voltage $V_{oc}$, whereas the second determines the short circuit current $I_{sc}$. The following formula is then used to establish the uncompensated power (Kacprzak *et al.*, 2005):

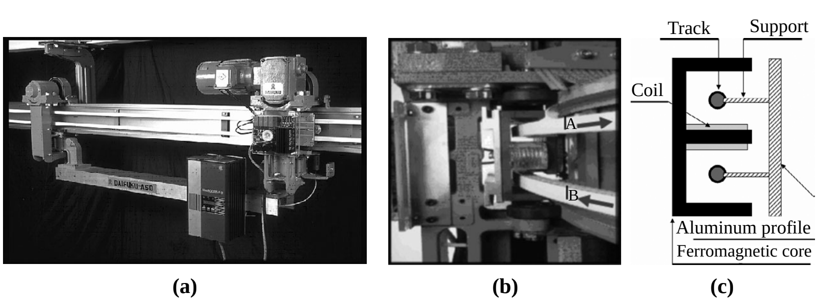


**Figure 2.**
Photos and a diagram of ICPT monorail system with E-pickup

$$S = QV_{\mathrm{oc}}I_{\mathrm{sc}} \tag{1}$$

where $Q$ is the quality factor introduced by Boys *et al.* (2000), $V_{\mathrm{oc}}$ is the open circuit voltage, and $I_{\mathrm{sc}}$ is the short circuit current. $V_{\mathrm{oc}}$ can be obtained from a numerical model where the conductivity of the pickup's coil is set to zero, while $I_{\mathrm{sc}}$ is usually computed from a model where a representative conductivity of the Litz-wired coil is substituted.

Moreover, an alternative formula could be used to obtain the apparent power:

$$S = Q\frac{I_1^2\omega\kappa^2(1-\mathrm{ICCF})}{\Re} \tag{2}$$

where $Q$ is the quality factor, $I_1$ is the value of the current in the track, ω is the angular pulsation, $\kappa$ is the coupling factor (Boys *et al.*, 2007), ICCF is the inter-conductor cancellation factor, and $\Re$ is the reluctance of the ferromagnetic core (Kacprzak, 2006a, b). A change in any variable present in equation (2) directly affects the power of the pickup and the impact of that change may be easily estimated. Thus, equation (2) facilitates both understanding and actual design/optimisation of pick-up systems.

During a design or optimisation process, three particular components of equation (2) may therefore be considered, namely $\kappa$, ICCF, and $\Re$. These components depend purely on the magnetic flux distribution, and may be estimated as follows.

The coupling factor is obtained as the ratio:

$$\kappa = \frac{\Phi_{\mathrm{M}}}{\Phi_{L2}} \tag{3}$$

where $\Phi_{\mathrm{M}}$ is the mutual flux linking the pickup coil and the track and $\Phi_{L2}$ is the total flux in the coil.

The ICCF may be found from a FEM analysis in which only one of the track's conductors carries the electrical current; such case is shown in Figure 3. The key point here is to determine the ratio of the magnetic flux which passes the coil, $\Phi_{\mathrm{coil}}$, to the magnetic flux which misses the coil, $\Phi_{\mathrm{cancelB}}$ (mainly through one of the pickup's "arms" as indicated in Figure 3.). Ultimately the magnetic flux $\Phi_{\mathrm{cancelB}}$ is cancelled if both conductors of the monorail track are carrying electrical current – thus this portion of the flux is "lost". This causes serious limitations to the overall power transferred by the pickup. As some pickups might be asymmetrical (Kacprzak, 2006a, b), ICCF is normally calculated as an average value from two models in which $I_{\mathrm{A}} = 0$ and $I_{\mathrm{B}} = 0$, respectively, as shown by equation (4):

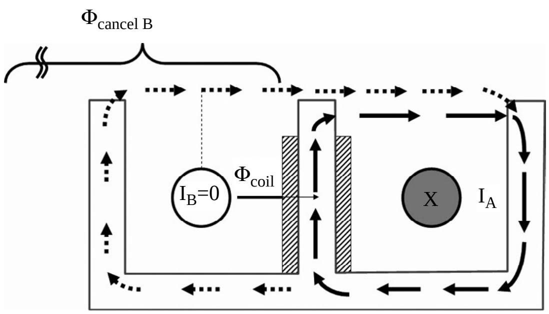


**Figure 3.**
E-pickup on monorail system with one conductor of the track carrying electrical current

$$\mathrm{ICCF} = \frac{1}{2}\left( \frac{\Phi_{\mathrm{coil}}}{\Phi_{\mathrm{cancel}B}}\bigg|_{I_B=0} + \frac{\Phi_{\mathrm{coil}}}{\Phi_{\mathrm{cancel}A}}\bigg|_{I_A=0} \right) \tag{4}$$

The reluctance of the total flux path that couples the pickup magnetic structure is given by:

$$\Re_c = \frac{N_1 I_1}{\Phi_{\mathrm{total\ \ coupling}}} \tag{5}$$

where $I_1$ is the magnitude of the track current, $N_1$ is the number of turns of the track, which in this case is $N_1 = 1$, and $\Phi_{\mathrm{totalcoupling}}$ is the total flux which is coupled with the pickup's ferrite.

## 3. Proximity effect in multiple pickup configurations

In a multiple pickup configuration the total power collected by the pickups is not simply proportional to the number of pickups, but depends also on the distance between the pickups. For example, if the distance between two E-pickups is very small, the power transferred by each E-pickup will be noticeably reduced. This phenomenon, as explained below, is caused by a mutual inductance existing between the pickups.

In order to define the proximity effect, as well as to quantify it, a finite element analysis was undertaken. Two E-pickups were analysed, where one (called the emitting pickup) was excited by an AC current, and the second one (called the receiving pickup) was working in an open circuit configuration. To clearly observe the magnetic field interference between the two pickups, the effect of the track's field was eliminated by setting the value of the primary current to zero, $I_1 = 0$. Figure 4 shows the configuration. The magnetic flux of the emitting pickup is denoted as $\Phi_{\mathrm{E}}$. The description $\Phi_{\mathrm{M\text{-}PE}}$ indicates the mutual portion of the flux $\Phi_{\mathrm{E}}$, which penetrates the receiving pickup. The magnetic flux of the receiving pickup is then designated as $\Phi_{\mathrm{R}}$. In this particular case $\Phi_{\mathrm{M\text{-}PE}} = \Phi_{\mathrm{R}}$, but it should be noted that $\Phi_{\mathrm{R}}$ may change if the number of emitting pickups increases. The proximity effect (PE) is defined as the ratio of $\Phi_{\mathrm{E}}/\Phi_{\mathrm{R}}$, and can be expressed as a percentage as shown by equation (6).

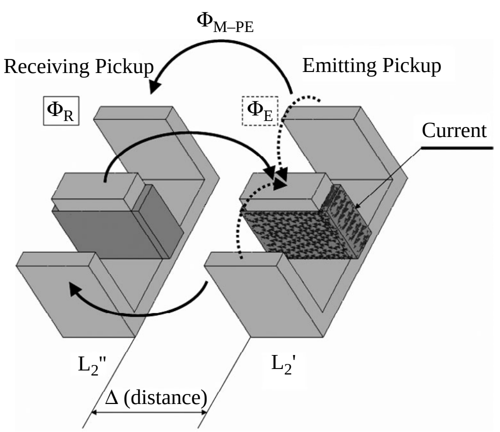


**Figure 4.**
Two E-pickups in proximity effect analysis

Figure 5 shows the changes of $\Phi_E$, $\Phi_R$ and PE as a function of the distance between the two E-pickups. The shape of all the curves confirms a nonlinear nature of this proximity effect:

$$\mathrm{PE} = \frac{\Phi_R}{\Phi_E} \times 100 \text{ per cent} \tag{6}$$

## 4. Improvements to the nonlinearity of ICPT systems

The easiest way to avoid the power drop in a multi-pickup configuration is to set a large distance between the pickups. However, such a solution may not be practical in all cases (Boys *et al.*, 2007). For example, in some installations there may simply not be enough space to do so. In this section, two innovative solutions are proposed to improve the nonlinearity of the multi-pickup configurations as well as to increase the power transferred by an ICPT system.

Since, the proximity effect is caused by the mutual flux between the emitting and receiving pickups, it seems possible to introduce a configuration in which mutual flux $\Phi_{M\text{-}PE}$ can be added to flux $\Phi_R$. This can be achieved, for example, if E-pickups are replaced by alternately directed Z-pickups as shown in Figure 6 (Kacprzak, 2006a, b).

As can bee seen, the use of two alternately-directed Z-pickups ensures a beneficial path for the mutual flux caused by the proximity effect $\Phi_{M\text{-}PE}$. However, existing ICPT monorail systems are not suitable to accommodate the alternate-direction configuration of Z-pickups. In practice, the track conductors are attached to an aluminium profile (Figure 2), which prevents any pickups from travelling in the area between the track conductors and the aluminium profile.

Thus, as an alternative, a split-type E-pickup configuration is proposed (Figure 7), which can be used on existing tracks without any limitations and with no need for modifications. In the design process of the split-type E-pickups, two objectives were attempted.

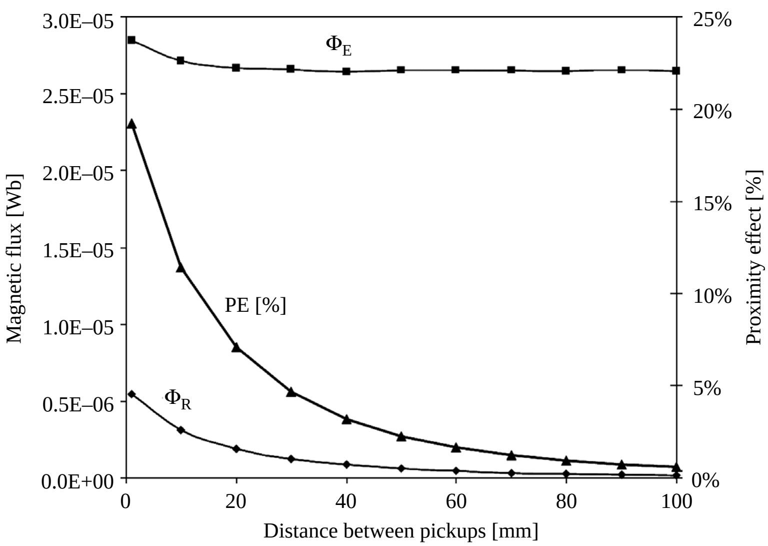


**Figure 5.** Magnetic flux and proximity effect versus a distance between two E-pickups

The first was to create a system with higher power transfer capability, which could be used on existing ICPT tracks; the second target was to ensure that the proposed configuration is not affected by the proximity effect.

Figure 7 shows the proposed split-type E-pickup. It was created from a standard E-pickup by dividing the ferrite and splitting it into two parts. As a result, the inter-conductor cancellation factor ICCF has been reduced, thus increasing the power of the pickup. Although inevitably the length of the pickup coil had to be increased, this has resulted in only 2 per cent power gain, whereas the total gain is far bigger and amounts to an impressive 26 per cent increase in power. The reason is the unique shape of the split-type E-pickup which reduces the proximity effect as the reluctance path for the mutual flux $\Phi_{M\text{-}PE}$ is much higher. Table I shows some of the most important parameters describing a conventional E-pickup and the split-type version.

The three described configurations, namely the E-pickup, Z-pickup and split-type E-pickup, were further analysed to compare their overall performance. The results are presented in the form of the graphs in Figures 8 and 9. Thus, Figure 8 shows the change of power as a function of the distance between the two pickups. As expected, the power of the alternately-directed Z-pickup configuration slightly increases when the pickups are close to each another. The performance of a split-type E-pickup system

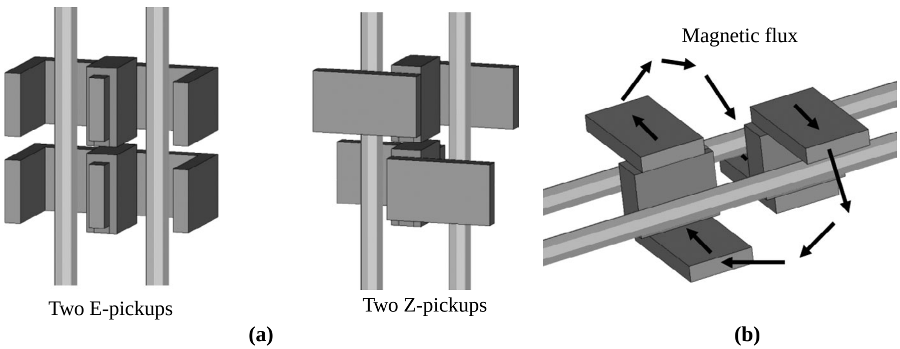


**Figure 6.**
Improved configurations (a) E pickups and alternate Z-pickups; (b) Magnetic flux path in alternate Z-pickup configuration

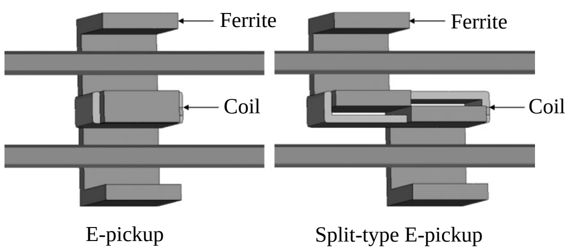


**Figure 7.**
E-pickup and split-type E-pickup

**Table I.**
Parameters of E-pickup and split-type E-pickup

| Type of pickup | ICCF | Power S (VA) | Power-to-volume of ferrite ratio (VA/mm$^3$) |
|---|---|---|---|
| E-pickup | 0.37 | 57.6 | 0.40 |
| Split-type E-pickup | 0.14 | 72.6 | 0.51 |

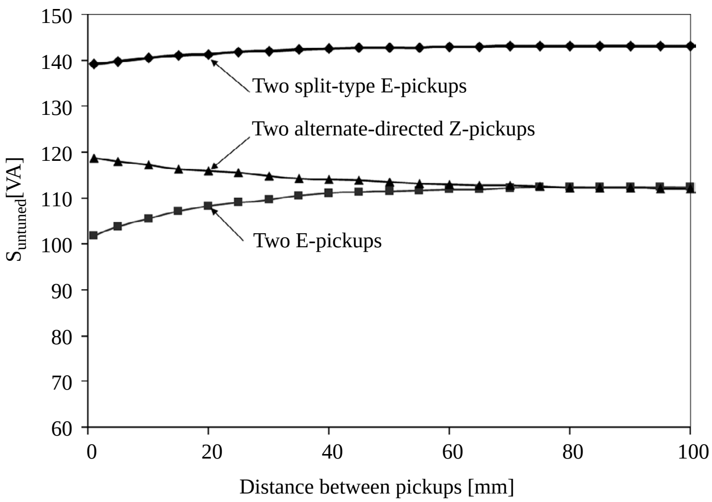


**Figure 8.**
Power from analysed ICPT multi-pickup configuration

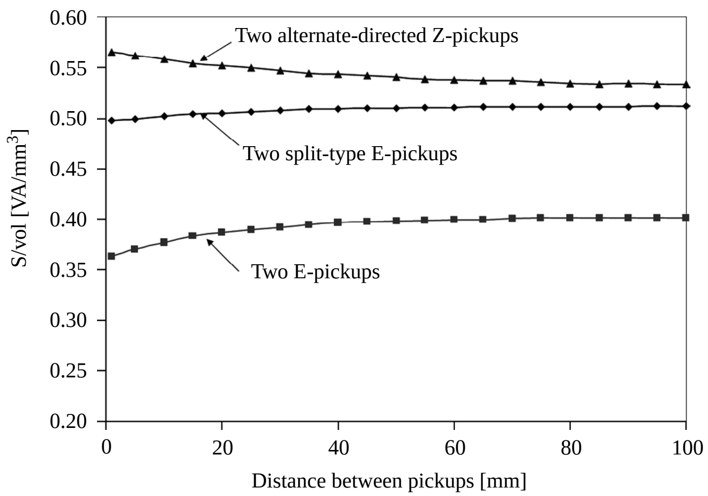


**Figure 9.**
Power to volume of ferrite ratio

is particularly satisfying: not only the proximity effect is reduced but the total power is also much bigger. Figure 9 shows the power to volume of ferrite ratio for all three configurations; here the two alternately-directed Z-pickups demonstrate the most efficient use of the ferromagnetic material, but the split-type E-pickup also shows significant improvement over the standard E-pickup configuration.

## 5. Conclusions

Careful analysis of magnetic field distributions is important in the design of modern power pick-ups to optimise the performance of magnetic circuits and benefit from available cancellation or reinforcement effects of various magnetic flux components.

It has been demonstrated that a multi-pickup formation of conventional E-pickups may lead to loss of power due to negative coupling between neighbouring pickups and that the phenomenon is nonlinear. The proximity effect has been defined and quantified. Two novel configurations for multi-pickup systems have been proposed, an alternately-directed Z-pickup and a spilt-type E-pickup, both showing improved linearity, increased total power and more efficient use of ferromagnetic material. The finite-element aided magnetic field simulation has proved indispensable in achieving difficult design objectives.

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