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Inductively Coupled Power Transfer
System Pickups

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An Improved Magnetic Design for Inductively Coupled Power Transfer System Pickups

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Abstract— This paper presents a new approach to the design of inductively coupled power transfer pickups using electromagnetic modeling techniques. As shown, significant improvements in the level of output power are able to be achieved for a given volume of ferrite by considering the field vectors in and around the ferrite and the power coil. The new design approach undertaken using 3-D simulations, is verified experimentally in the laboratory.

Index Terms—Electromagnetic coupling, Industrial power systems, Magnetic analysis.

I. INTRODUCTION

INDUCTIVELY coupled power transfer (ICPT) technology has found application in systems, where energy transfer without mechanical contact is required. Such systems are commonly used in all ranges of power supply devices for clean rooms, battery charging modules, monorail transportation, and biomedical apparatus [1].

A typical ICPT system comprises a track carrying a primary current I_1 , and a pickup designed to collect power along the track as shown in fig. 1. [2].

A common pickup configuration used in monorail ICPT systems is the E-pickup illustrated in figure 2. The ICPT track has a single phase wire with its return path placed in close proximity. The pick-up is constructed such that it takes power from both halves of the track. Due to its simple and practical shape, the E-pickup has been widely used by industry for many years and over time has become one of the most popular pickup shapes. However, industry demands for more powerful pickups, without actually building them any larger and heavier, has led to a rethink regarding the best and most appropriate magnetic structure for the application.

This paper investigates an alternative pickup design that focuses on achieving significant increases in available output power with only simple modifications to the existing E-pick, using knowledge of the magnetic field paths surrounding the ferrite and the secondary pickup coil.

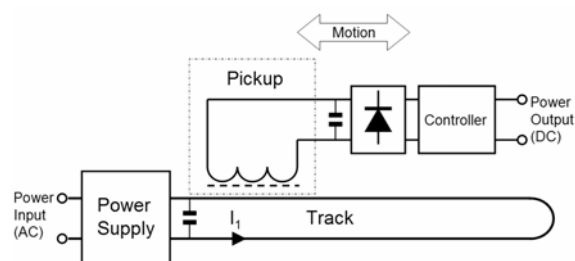


Fig. 1. ICPT system – monorail approach

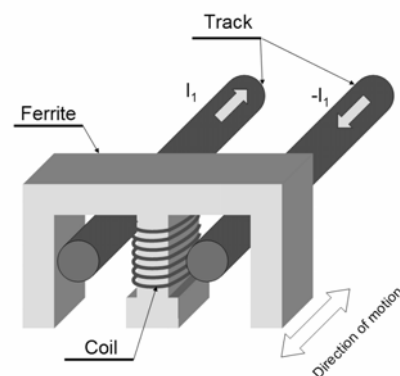


Fig. 2. E-pickup for monorail applications

The paper begins by analysing the well know E pick-up structure using 3-D magnetic modelling techniques. It describes a simple method whereby the apparent power of any pick-up can be determined from such simulations and verified by measurement. The modeling package allows the field lines to be analysed to show where improvements are possible. The paper then introduces a modified pick-up shape with significantly better field capturing characteristics.

II. ANALYSING THE STANDARD E-PICKUP

A typical E-pickup with dimensions given by Figure 3 was analysed using Finite Element Methods (FEM) to calculate its apparent power. The ferromagnetic material used in this model is NKK 50EF1000. The value of the track current is $I_1=80A@ 10kHz$. The apparent power can be calculated according to [3]:

$$S = V_{oc} I_{sc} \quad \dots(1)$$

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Where V_{oc} is the open circuit voltage of the secondary coil and I_{sc} is the short circuit current of this coil.

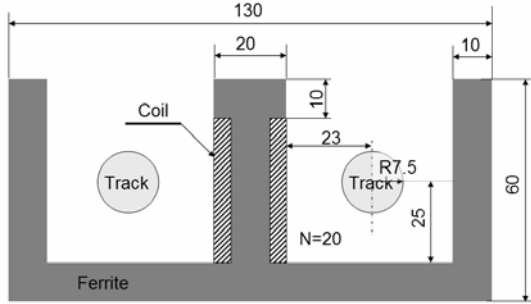


Fig. 3. E-pickup dimensions, ferrite thickness $Z=60\text{mm}$

In order to obtain the value of V_{oc} from the FEM analysis, a 3D numerical model was created. The pickup's ferrite was analyzed, with the conductivity of the coil set to zero. Based on the resultant magnetic flux density B (shown in Fig. 4)

The open circuit voltage was then calculated using:

$$V_{oc} = NB_{avg}A_{B\perp}\omega \quad \dots(2)$$

Where N is the number of turns, B_{avg} is the average value of the magnetic flux density B in the ferrite under the coil, and $A_{B\perp}$ is the cross-section of the ferrite perpendicular to the vectors of the magnetic flux density B .

I_{sc} was obtained from a separate numerical model, where the middle leg of the ferrite E core is assumed to be surrounded by a solid copper coil (achieved by setting the coil's conductivity to that of copper $\sigma_{cu} = 5.8 \times 10^7 \text{ S/m}$). Figure 5 shows the coil installed on the ferrite.

Using the above, the short circuit current is given by:

$$I_{sc} = \frac{J_{avg} \cdot A_{I\perp}}{N} \quad \dots(3)$$

Where J_{avg} is the average value of the current density in the solid coil and $A_{I\perp}$ is the cross-section of the solid coil perpendicular to the flow of the current.

As part of the output of the simulation, the 3D magnetic field line vectors can be visualised on screen and analysed. Ideally the magnetic design should ensure the greatest concentration of flux through the middle ferrite leg where the power coil exists. As shown in figure 6 two main paths exist for these field lines. What is also apparent here is that there is a region directly above the central ferrite leg where the field vectors oppose each other in the air. The resulting field cancellation is directly responsible for a reduction in the flux density within the central core, which in turn significantly lowers the open circuit voltage of the coil from what might be expected if this field cancellation was not present.

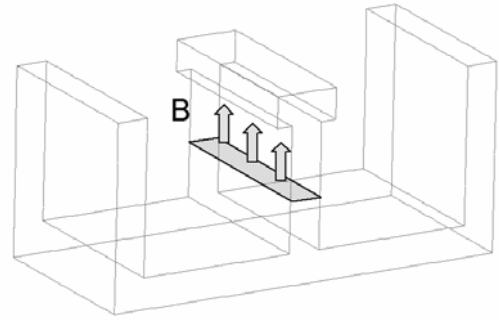


Fig. 4. Magnetic flux density for open circuit voltage analysis

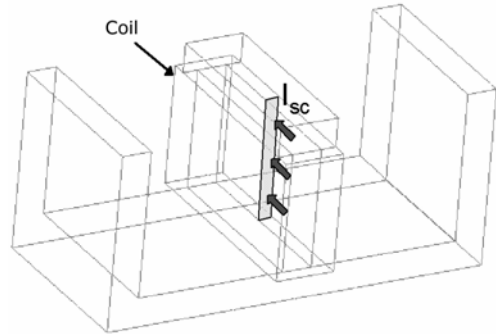


Fig. 5. Model for short circuit current analysis

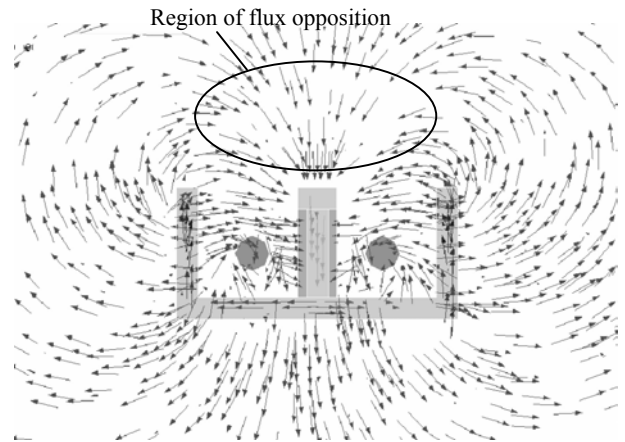


Fig. 6. Magnetic field of E-pickup

III. AN IMPROVED PICKUP DESIGN

A magnetic design that substantially eliminates any field cancellation should result in a much higher power pickup without the need for increasing the amount of ferrite. The proposed pickup is shown in figure 7 and because its shape resembles the letter "S", it is called an S-pickup.

Using an identical analysis approach to that described earlier for the E pick-up, this new pick-up structure can be directly compared with the standard E-pickup. The new S-pickup has exactly the same volume of ferromagnetic material and is assumed to have an identical coil with the same number of turns ($N=20$).

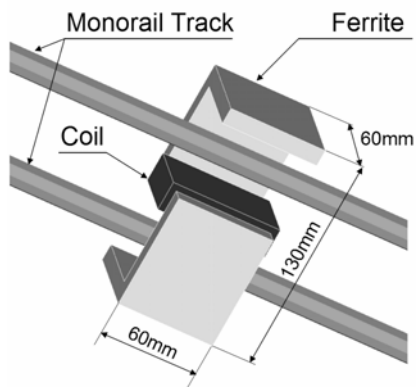


Fig. 7. The proposed S-pickup mounted on a monorail track

Figure 8 shows the field lines around the proposed S-pickup. As can be noted, the vectors do not appear to directly oppose each other in the air and consequently the magnetic field density in the central arm where the power coil is positioned should be at a maximum.

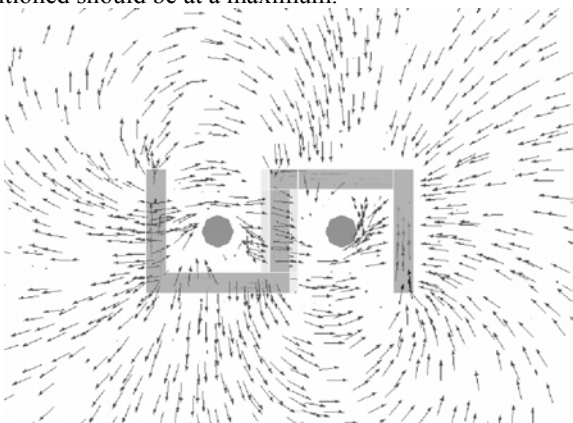


Fig. 8. Magnetic field of S-pickup

Table 1 compares the simulated output voltages and currents of the E and S pickups. The results, show that the S-pickup delivers almost twice as much power as the E-pickup. As expected the biggest difference is in the open circuit voltage which is increased by a further 78% as a result of this redesign. Surprisingly there is also a 10% increase in the short circuit current that arises because the new ferrite structure effectively results in a lower reluctance mutual path and less leakage.

TABLE 1
PARAMETERS OF E AND S PICKUPS

| | S-Pickup | E-Pickup |
|----------|----------|----------|
| V_{oc} | 35.7 V | 20.1 V |
| I_{sc} | 4.4 A | 4.0 A |
| S | 158.5 VA | 80.8 VA |

The advantage of the S-pickup comes from the way in which it handles the flow of the magnetic flux. When comparing the E and S pickups, each has the same volume of ferrite, and equally long air-gaps, however in the case of the S

pickup the ferrite is better used in the areas of high magnetic field concentration.

IV. MEASURED VERSUS SIMULATED S AND E POWER PICKUPS

An experiment was carried out to verify the concept of a high power S-pickup as well as to find the correspondence between the numerical analysis and the physical measurement.

Using two identical ferromagnetic elements, both E and S pickups were constructed as shown in fig. 9. The two pickups were made from the same volume of ferrite and had identical coils with number of turns $N=11$. The value of the current in the track was $I_1=70.3A @ 15.1kHz$.

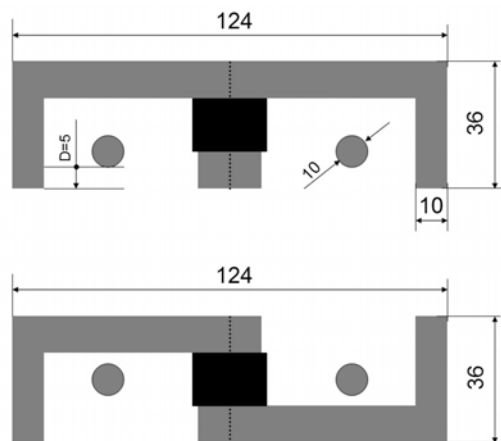


Fig. 9. E and S pickups

Normally such pickups are sited on a moving bogie as part of a monorail system, and little variation is expected between the track and ferrite except as a result of variances in the construction of the track. As such the pickup position is normally well constrained relative to the track cable, except when the vehicle (bogie and pickup) moves around a corner, as shown in figure 10. Under such conditions the distance between the track and ferrite can shift. This movement distance labelled 'D' in figure 9(a) will negatively affect the power transfer and is also investigated here.

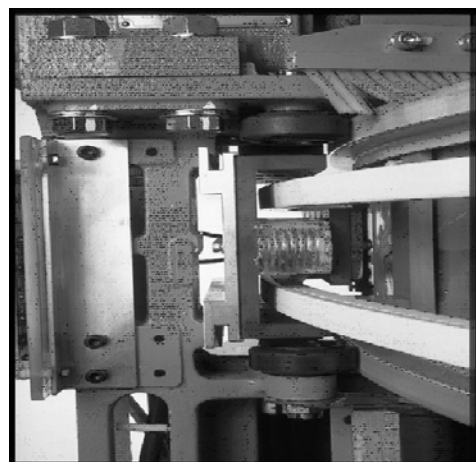


Fig 10. A bogie with pickup sited on a monorail as it moves around a corner

In the analysis a variation of 5 mm in D in figure 9(a) was assumed possible. This same variation was measured and simulated for the S pickup. In this case the track cable rests against the ferrite on one side. Results of the calculated output power are shown in figure 11.

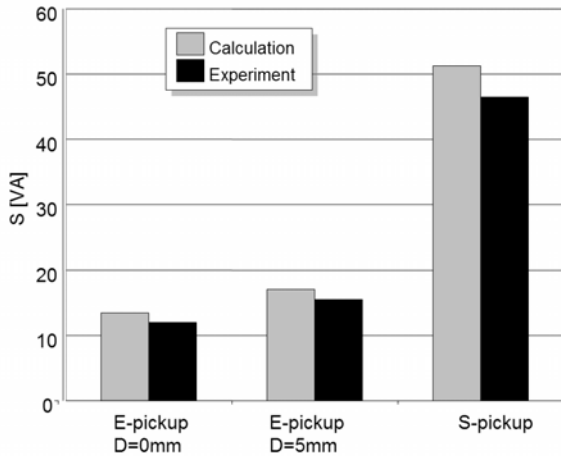


Fig. 11. Comparison of results

As noted, there are slight variations between simulation and experiment. These arise because several practical features were not added into the simulation, any of which would slightly decrease the expected power, but not the simulated trends. The actual ferrite had chamfered edges and a small air gap was present between the two ferrite elements. Furthermore the coil winding was not completely symmetrical with slight variations in spacing between adjacent wires. In addition, the coil created in the numerical model represented a solid copper element, instead of the litz-wire. This assumption simplifies the modelling, however it also causes a small calculation error (<5%). Despite these variations the simulations accurately predict the experimental trends. The variation in simulated output power as a result of track movement (from D=5mm to 0mm) is a 21.5% drop in power. This compares with a measured drop in power of 23.1%. In the case of the S-pickup, there was no noticeable change in either the measured or simulated power when the track position was varied; in consequence only one power value is shown in figure 11.

The power increase achieved by moving from an ideally placed E pickup to an S-pick up is calculated from simulation to be an addition of 201% (three times more power is possible). By experiment this is determined to be an increase of 199.2%.

As noted, this increase in power is even greater than that disclosed in section 3. The reason for this is that a practical E pickup always includes the foot at the base of the coil (shown in figures 3, 4 and 5), and this foot adds 40-50% improvement in the power output of the pickup. When the experimental pickup was constructed, this foot was not included to ensure that the ferrite pieces were identical in both the E and S pickups. Thus an S pickup would be expected to provide a power increase of 2 times compared to a commercial E-pickup with identical ferrite volume as predicted earlier.

V. CONCLUSIONS

A careful analysis of the field cancellation factors appears to be crucial in the design of modern power pick-ups. Consequently there is a need to re-analyse pickups used in such applications to ensure that where possible such field cancellation can be avoided. The presented S-pickup is an interesting alternative to the E-pickup, and if it can be applied in an ICPT system it can provide almost double the power output for a given volume of ferrite, at no increase in cost. Furthermore the S-pickup is not found to be as sensitive to movements in the track position relative to the pickup ferrite.

VI. REFERENCES

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