Calculation of magnetic field and forces in electromagnetic devices for separation of steel sheets

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Abstract: The surfaces of steel sheets delivered by steelworks in packs are generally oiled. To separate them a U-shaped DC electromagnet or permanent magnet can be applied. Using the finite-difference method the 3-dimensional field distribution and forces on the top sheet have been calculated. Some remarks about the computer aided design of electromagnetic devices for the separation of steel sheets have also been included.

List of principal symbols

B = magnetic flux density
F = force
f = force density
g = thickness of steel sheet
H = magnetic field strength
J = current density
k_f = coefficient of static friction
l = length of stack
l_z = arm of a force
S = surface
T_{mn} = Maxwell's stress tensor
x, y, z = Cartesian co-ordinates
δ = thickness of distance layer
μ = magnetic permeability (μ_0 = permeability of free space)
Φ = magnetic scalar potential
Θ = magnetomotive force

1 Introduction

The magnetic separation of steel sheets can be used in many manufacturing processes. Steel sheets are usually oiled and are delivered by steelworks in packs. An oil layer between adjacent sheets glues them together. This cohesion force makes it impossible to handle the sheets. It is necessary to separate them before further processing such as cutting, stamping, forming or pressing. The magnetic field is regarded as a modern, effective and simple way to separate the ferromagnetic sheets.

Fig. 1 shows the principle of operation of a piece of equipment used for the magnetic separation of steel sheets. One or more U-shaped permanent magnets touch the flank of the stack of sheets through a nonmagnetic distance plate. At least one of the top sheets is separated from the stack as a result of the action of the magnetic field. It makes it possible to transport the separated sheet along a production line.

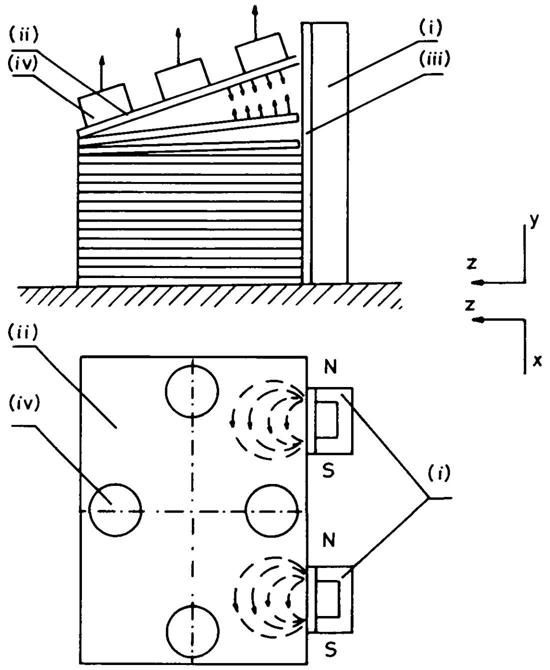

Fig. 1. *Principle of operation of a machine which separates steel sheets magnetically*
(i) permanent magnet or DC electromagnet
(ii) steel sheet
(iii) nonmagnetic distance layer
(iv) vacuum cup of a lifting crane

The configuration of the magnetic field produced by a permanent magnet or a DC electromagnet should enable the magnetic force to be high enough to lift up one of the top sheets. It means that the distribution of the magnetic field should be known to estimate forces acting on the sheets.

As far as the authors are aware, the papers published so far pertain only to the conception and industrial application of U-shaped magnets for the separation of steel sheets [1]. An attempt to analyse the electromagnetic effects and design problems has been made in an earlier paper [2].

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2 Calculation of the magnetic field

The magnetic force lifting up a sheet is produced when the difference between magnetic flux density normal components at the upper and lower surface of a sheet takes a positive value. The co-ordinate system is shown in Fig. 1. The magnetic field distribution in the neighbourhood of the top sheet is of particular importance. The field distribution must be regarded as 3-dimensional. It is necessary to take into account the inhomogeneity (air-ferromagnetic sheets) and magnetic nonlinearity of the ferromagnetic sheets. The magnetic field in the equipment analysed for the separation of the sheets is described by the following set of equations:

$$\operatorname{curl} \boldsymbol{H} = \boldsymbol{J} \tag{1}$$

$$\operatorname{div} \boldsymbol{B} = 0 \tag{2}$$

$$\boldsymbol{B} = \mu \boldsymbol{H} \tag{3}$$

According to Müller and Wolf [3], the resultant magnetic field can be treated as a sum of two fields:

$$\boldsymbol{H} = \boldsymbol{H}_s + \boldsymbol{H}_p \tag{4}$$

where the source component $\boldsymbol{H}_s$ is chosen to satisfy the equation

$$\operatorname{curl} \boldsymbol{H}_s = \operatorname{curl} \boldsymbol{H} = \boldsymbol{J} \tag{5}$$

It allows us to make use of the magnetic scalar potential which is defined as

$$\boldsymbol{H}_p = -\operatorname{grad} \Phi \tag{6}$$

Hence, the analysis of the magnetic field can be obtained by solution of the following differential equation:

$$\operatorname{div} \mu \operatorname{grad} \Phi = \operatorname{div} \mu \boldsymbol{H}_s \tag{7}$$

First, the range of calculation and the boundary conditions are to be determined, and then an equivalent set of linear equations with regard to eqn. 7 is to be considered. For this purpose the method of a successive overrelaxation [4] has been applied and the package of SHEETS computer programs has been prepared [5]. On the basis of the computed distribution of magnetic scalar potential the magnetic field strength distribution has been obtained.

The nonlinearity of ferromagnetic material has been included by adding an additional iteration cycle, in which the present value of magnetic permeability is compared with the previous value. When the difference is less than a given error criteria, the iteration is stopped.

3 Calculation of forces

The force system acting on the top sheet is shown in Fig. 2. The equation expressing the equilibrium of the moments is written as

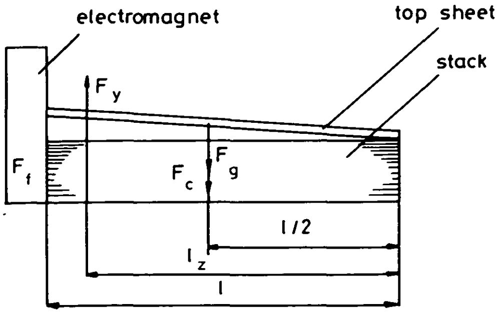


Fig. 2. *Forces acting on a single sheet*

$$F_y l_z = [0.5(F_g + F_c) + F_f]l \tag{8}$$

where F_y is the normal component of lift force acting on the sheet; l_z is the arm of the F_y force; F_g is the gravity force of sheet being considered; F_c is the cohesion force on the sheet; F_f is the force of friction between sheet edge and the magnetic; l is the length of the stack.

When the left-hand side of eqn. 8 is higher than the right-hand side, the sheet will move up. The motion will cease when the left-hand side is equal to right-hand side. The cohesion force F_c can be estimated on the basis of experimental data.

A well designed U-shaped permanent magnet or electromagnet should ensure an appropriate lift force F_y. To evaluate the force F_y, all the moments in eqn. 8 are to be analysed. For a given type of sheet the expression $F_g l$ is known. The force of static friction is expressed by the formula

$$F_f = k_f F_z \tag{9}$$

in which k_f is the coefficient of static friction, and F_z is the tangential component of magnetic force acting on the sheet (Fig. 2).

This simplified analysis shows that it is necessary to calculate both the normal component F_y of the magnetic force acting on the sheet, its point of application, and the tangential component F_z of this force.

The force of a ferromagnetic element placed in a magnetic field can be expressed as a surface integral around a closed area S embracing this element [6, 7]. This force can be determined with the help of Maxwell's stress tensor T_{mn} [8, 9], i.e.

$$\begin{aligned} \boldsymbol{F} &= \int_S T_{mn} \boldsymbol{n} \, dS \\ &= \int_S [\mu_0 (\boldsymbol{H} \cdot \boldsymbol{n}) \boldsymbol{H} - 0.5 \mu_0 H^2 \boldsymbol{n}] \, dS \\ &= \int_S \boldsymbol{f} \, dS \end{aligned} \tag{10}$$

where $\boldsymbol{n}$ is the outward-directed unit vector normal to the surface S, and the force density is equal to

$$\boldsymbol{f} = \boldsymbol{i} f_x + \boldsymbol{j} f_y + \boldsymbol{k} f_z \tag{11}$$

In a Cartesian co-ordinate system the area of integration is chosen to be rectangular. The components of the vector $\boldsymbol{f}$ can be expressed with the aid of the components of magnetic field strength vector, which have been calculated earlier. For the plane $x0z$ the components of the force density vector have the following form:

$$\begin{aligned} f_x &= \mu_0 H_x H_y \\ f_y &= 0.5 \mu_0 (H_y^2 - H_x^2 - H_z^2) \\ f_z &= \mu_0 H_y H_z \end{aligned} \tag{12}$$

Hence

$$\begin{aligned} F_x &= \int_S f_x \, dS \\ F_y &= \int_S f_y \, dS \\ F_z &= \int_S f_z \, dS \end{aligned} \tag{13}$$

The forces F_x on each of two edges of the top sheet are in opposition, so that these forces have no practical meaning.

To find the arm of F_y knowledge of the F_y distribution along the z axis is necessary. It has been done by dividing the sheet into strips which are perpendicular to the z axis. The force on this strip has been calculated in similar way as above. Hence, the arm of F_y is equal to

$$l_z = \sum_{i=1}^{k} F_{yi} z_i \Big/ \sum_{i=1}^{k} F_{yi} \tag{14}$$

where F_{yi} is the normal force on a strip and z_i is the point of application of F_{yi}.

4 Computer program

The computations have been done with the help of the SHEETS package [5]. It consists of three integral parts: a preprocessor, a solver, and a postprocessor. The preprocessor finds values of the source component H_s of magnetic field strength and fixes an initial distribution of magnetic permeability. The solver is used to solve eqn. 7 using the finite difference method. Then, on the basis of the calculated distribution of the magnetic field, the components of force and the co-ordinates of its application point are determined. The forces and co-ordinates are calculated by the postprocessor. The postprocessor enables the field and force distributions to be plotted too. The distribution of the H_z component of magnetic field strength in the nonmagnetic distance layer between the poles and the stack is plotted in Fig. 3. The distribution of the H_y component at the surface of the top sheet is plotted in Fig. 4. The plots give the tangential and normal field strength distribution in the magnetic circuit and indicate the range of effective operation of the equipment. The computer software package can also calculate other magnetic quantities and winding parameters.

5 Computer-aided design

There are two methods of using computer-aided design (CAD) to design electromagnetic devices:

(i) a choice of optimum performance of magnet as a result of performing the multiple analysis of magnetic field

(ii) determining the performance of a magnet from the synthesis of magnetic field.

The method of CAD proposed by the authors is based on the analysis of magnetic field.

The magnetic flux density at the active surface on the magnet, its arrangement with regard to the top surface of the stack, and the thickness of the nonmagnetic distance layer between the stack and the poles of the magnet has the biggest influence on the value of useful force needed for the separation of the sheets. In the case of an electro-

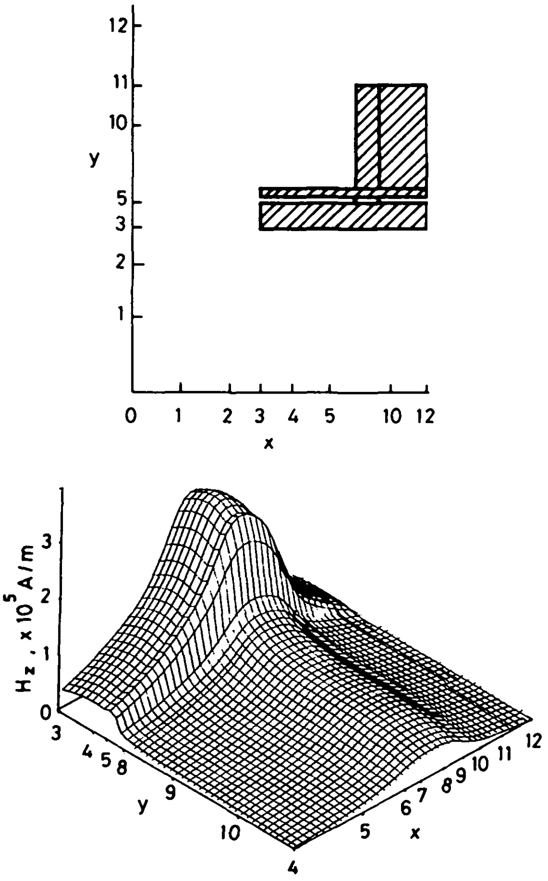


Fig. 3 *3-dimensional distribution of tangential component H_z of magnetic field strength in distance layer between stack and magnet pole*

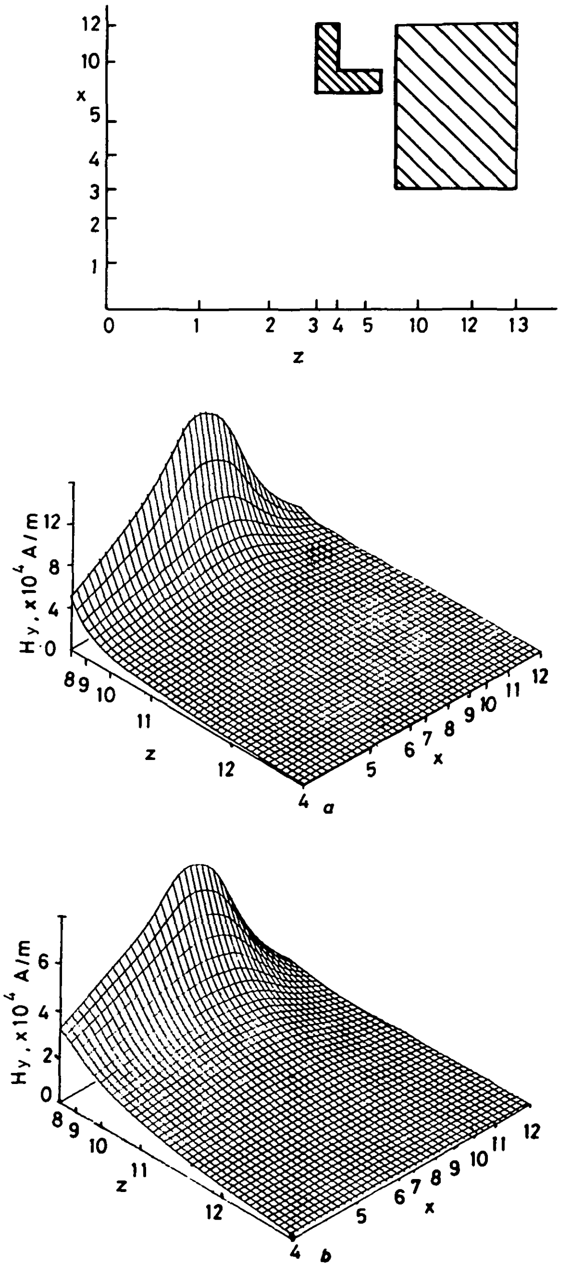


Fig. 4 *3-dimensional distribution of normal component H_y of magnetic field strength at the top sheet*

a Upper side
b Lower side.

magnet, the nonmagnetic gap is proportional to the MMF of the winding. Although the plot of lift force against MMF is approximately linear (Fig. 5) the influence of flux density and magnet setting on the lift force is more complicated.

The choice of the nonmagnetic distance layer thickness is very important. The smaller the thickness the higher the lift force. On the other hand, there is a critical value of thickness below which the attractive force between poles of the magnet and the sheets makes it impossible to separate them. In the extreme case, i.e. when no distance layer exists, sheets stick to the poles (Fig. 6). The lift and attractive forces are shown in Fig. 7 as functions of distance layer thickness at constant sheet thickness. The optimum value of the distance layer thickness falls in the range $4 < \delta < 8$ mm.

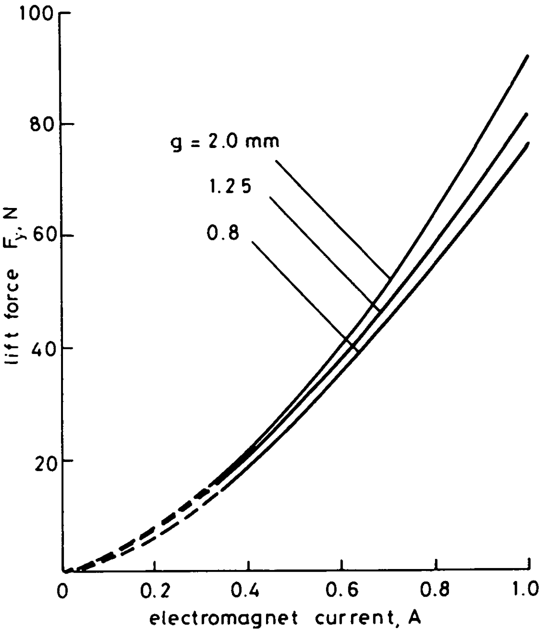
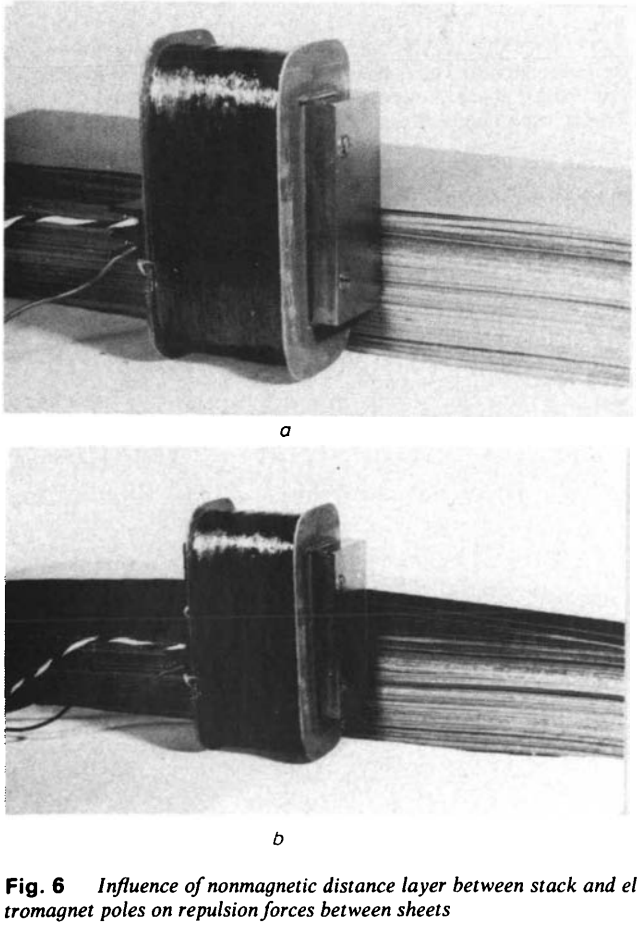


Fig. 5 *Influence of the electromagnet current on the lift force F_y at various sheet thickness g*



a

b

Fig. 6 *Influence of nonmagnetic distance layer between stack and electromagnet poles on repulsion forces between sheets*

a Without distance layer
b With distance layer

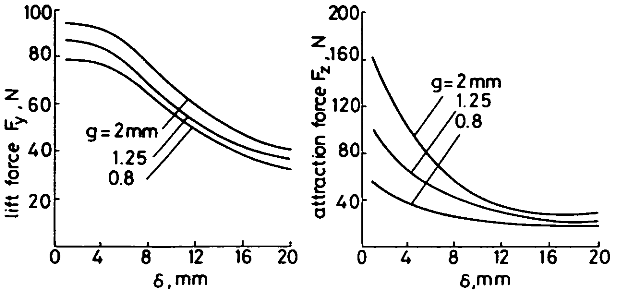


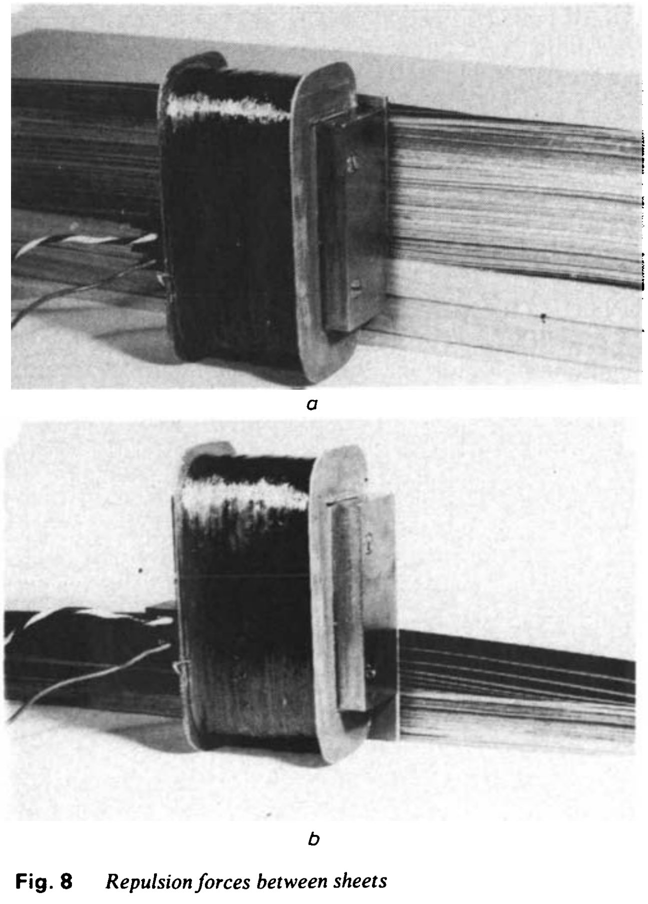
Fig. 7 *Lift force F_y and attraction force F_z against nonmagnetic layer thickness at various sheet thickness g*

Electromagnet current = 1 A, length of yoke = 110 mm, width of poles = 25 mm

The influence of the position of the magnet in relation to the top of stack is shown in Fig. 8. The lift force vanishes when the stack height is equal to or higher than the length of magnet core (in y direction). It has been confirmed by experiment that the length of magnet core equal to 1.3 … 1.4 × stack height ensures, in practice, a constant value of lift force, independent of the number of sheets.

The distribution of magnetic flux density B_z in the distance layer (nonmagnetic gap) along the axis of pole symmetry obtained from calculation and measurement is shown in Fig. 9.

As has been already mentioned, the CAD of a permanent magnet or electromagnet involves a number of



a

b

Fig. 8 *Repulsion forces between sheets*

a In the end region of core
b In the lower part of core

iterations, repeated many times. It is possible to reduce the number of iterations which means that the calculation time is reduced, by the application of appropriate mathematical methods and by the correct choice of input data. In the case of an electromagnet, the initial value of the MMF can be evaluated as $\Theta = B_c \delta/\mu_0$, where B_c is the value of magnetic flux density in the core. It is recommended to start with B_c close to the saturation magnetic flux density. The main aim of the calculation is to obtain a lift force F_y which satisfies eqn. 8. It is easy to affect the lift force in next iteration e.g. by changing the MMF or the distance layer thickness. Other dimensions, such as length of yoke and height of poles do not affect F_y much. These dimensions allow the space which is necessary for the winding to be increased or decreased. The winding calculation is the same as for other types of DC electromagnets.

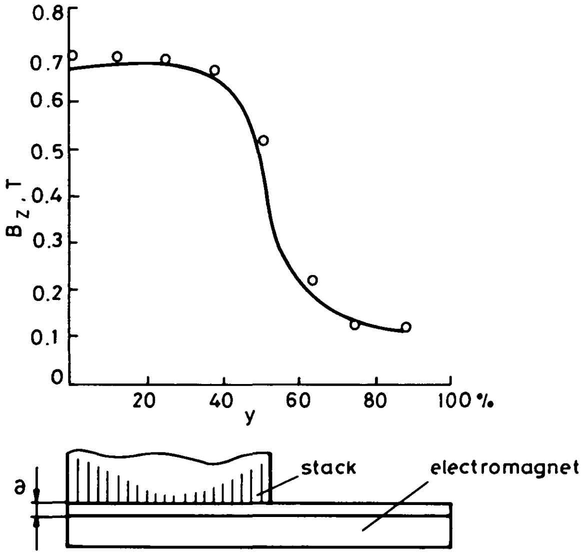


Fig. 9 *Distribution of magnetic flux density B_z along the pole symmetry axis*

o o o o measurement
——— calculation

6 Conclusions

The proposed methods of magnetic field analysis and calculation of forces in magnetic field acting on ferromagnetic sheets are adjusted for the CAD of an equipment for the separation of steel sheets. The magnetic field strength distribution is computed with the aid of the finite difference method. The methods of calculating the fields and forces which have been presented can be applied both in the case of permanent magnets and DC electromagnets. The experimental tests are in good agreement with calculated results [5], e.g. Fig. 9.

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Erratum

PAVITHRAN, K.N., PARIMELALAGAN, R., SRIDHARA RAO, G., and HOLTZ, J.: 'Optimum design of an induction motor for operation with current source inverters', *IEE Proc. B, Electr. Power Appl.*, 1987, **134**, (1), pp. 1–8

In the first paragraph of Section 7.2 on page 7, 'Fig. 5*d*' should read 'Fig. 6'.

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