Optimizing a transformer driven active magnetic shield in induction heating

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Abstract

Purpose – To design an optimal active shield for the mitigation of the magnetic stray field around an induction heating device.

Design/methodology/approach – The active shield consists of several compensation coils in series and generates a counter field opposite to the main field. One extra compensation winding – the “generating compensation winding” (GCW) – is positioned close to the excitation coil and works as the secondary winding of a transformer. The power in this winding is used to drive the other compensation coils (the active shield), which are the load of the transformer. A circuit with passive components is inserted between the GCW and the other compensation coils. The shield is optimal if it achieves a high field reduction, while the energy dissipation is low. By using a genetic algorithm (GA) that minimizes an objective function, the optimization algorithm finds the optimal geometry and the optimal current for the GCW and the other compensation coils. The objective function uses time harmonic and axisymmetric finite element calculations.

Findings – The transformer driven active shield reduces the magnetic field effectively. It is cheap and easy to build, but it works well only for one frequency.

Research limitations/implications – The shield is sensitive to tuning of the passive circuit and to changes in the frequency of the induction heater.

Practical implications – This transformer driven shield is an alternative for the classical active shield with external power supply.

Originality/value – An active shield that does not need an external power supply is a cheap solution for the shielding of magnetic fields.

Keywords Electromagnetic induction, Heat conduction, Finite element analysis, Optimization techniques

Paper type Research paper

1. Introduction

Due to the high magnetic field, needed to heat workpieces in induction heating, a magnetic stray field is created in the region surrounding the heating device. The operator of the equipment as well as the electronic apparatus may be exposed to high magnetic fields (Adriano et al., 2002; Floderus et al., 2002). As the fields can be significantly higher than the reference levels indicated by the ICNIRP-Guidelines (1998), the magnetic field should be mitigated using three techniques (Pettersson, 1996) applied to transmission lines:

This work was supported financially by the FWO-projects G.0309.03 and G.0161.02 and by the IUAP project P5/34 of the Belgian government.
• reconsideration of the induction heater design;
• passive shielding, using materials with limited electromagnetic losses within the shield (Schulz et al., 1988); and
• active shields: proper currents in a number of compensation coils generate counter fields opposite to the main one to be reduced (Hiles et al., 1998). Figure 1(a) shows the principle.

Next to the low energy dissipation in the shields, two other constraints should be taken into account: the influence on the heating process must be minimal and the workpiece in the induction heater must remain accessible.

The paper (Sergeant et al., 2003) describes an optimization method to find the optimal active shield, possibly combined with a passive shield, that reduces the stray field of a 1 kHz induction heater with given geometry and material properties in a defined area. However, both shields have “economic” disadvantages: in the passive shield, the eddy currents and/or hysteresis losses cause unwanted energy dissipation. The active shield is expensive and dissipates energy too: it needs a controller that continuously calculates the optimal compensation current and a convertor or amplifier to generate this current.

In this paper, the passive shield of the 1 kHz induction heater is replaced by a winding, similar to the capacitor compensated circuit in Walling et al. (1993). The power induced in this “generating compensation winding” (GCW) is used to drive the active shield (Figure 1(b)). This GCW becomes the third winding of the transformer in Figure 2. The first winding is the excitation coil with main inductance $L_{me}$, stray inductance $L_s$ and resistance $R_e$. The excitation current is an alternating current with constant amplitude that creates the main flux for the heating process. The second winding is the conducting workpiece: a short-circuited winding that reduces the main transformer flux. The third winding is the GCW. Its generated current $I_{gcw}$ and voltage $V_{gcw}$ are modified by an electric circuit and then provided to the other compensation

![Figure 1. Principles of active and passive shielding](image)

Notes: (a) the passive shield dissipates the induced power and the active shield needs an external power supply (b) the passive shield is a transformer winding that drives the active shield
coils. These three windings of the transformer are coupled by mutual inductances $M_{ew}$, $M_{eg}$, and $M_{wg}$, and are shown in Figure 2 by double arrows. Actually, the compensation coils are also coupled with the transformer coils. Thus, the active shield is modelled by the resistance $R_L$, the inductance $L_{at}$, and the voltage source $V_{L}$. The latter represents the voltage induced in the main inductance $L_m$. As the short-circuited workpiece cancels the major part of the main excitation flux, the voltage in the GCW is induced by the remaining "stray flux": the transformer is a "stray flux transformer".

Sections 2-4 describe the algorithm that optimizes the active shield and GCW geometry and the currents in all compensation coils, for a given geometry of the induction heater. An experimental set-up of an induction heater with the same geometry was built. In Section 6, the simulation results of Section 5 are verified by comparing the simulation results with measurements on the set-up. Finally, Section 7 investigates the dynamic behaviour of the GCW and active shield.

2. Overview of the calculation method
To reduce the stray field in a defined area – the target area – the optimal positions of the compensation coils and the currents in the coils must be identified from a proper inverse problem. The used electromagnetic model of the induction heater is chosen to be linear. The presented method to solve the inverse problem consists of two parts: an optimization part – a genetic algorithm (GA) that minimizes an objective function – and a post-processing part.

The optimization part runs a GA (Fogel, 1994) that optimizes the positions of the GCW and the compensation coils by iteratively evaluating an objective function and trying to minimize it. During each function evaluation, the GCW and the compensation coil positions are fixed. The compensation current, the GCW current (for all coils in series) and the numbers of coil turns are found by an inner optimization loop as described in Section 3. The GA applies inequality constraints to its input arguments to limit the number of possible coil positions. It terminates if the time limit is exceeded, if the maximum number of generations is reached or if the mean of the objective values
does not change any more within a certain tolerance. Further details about the GA and the constraints are explained in Sergeant et al. (2003).

In the post-processing part finally, a finite element (FE) calculation with complete modelling of all shields is executed with high accuracy, providing full access to all electromagnetic variables in the whole domain (not only in the target area), for post-processing purpose.

3. The objective function

3.1 Overview

The objective function calculates the “cost” of an active shield (consisting of a number of compensation coils in series) driven by a GCW.

The flowchart of the objective function is shown in Figure 3. To optimize the compensation current, the function needs the field distributions of the excitation coil, the GCW and each of the $N$ compensation coils. Here, a FE model – explained in Section 4 – is used to calculate and save[1] the needed field distributions, the resistances and the inductances of the coils. Once all necessary field distributions gathered, the objective function searches the optimal compensation current $I_L$, the optimal GCW current $I_{gcw}$ and the optimal numbers of coil turns $t_i$ by using an inner GA, nested within the objective function of the main algorithm.
The inner objective function first calculates the optimal current $I_L$ in the active shield for given numbers of turns and given amplitude and phase of $I_{gcw}$. Therefore, the field distributions of excitation coil, GCW and all compensation coils are used in a least squares routine that is described in Sergeant et al. (2003). Next, the components of the electric circuit are searched so that the given GCW current $I_{gcw}$ and corresponding induced voltage $V_{gcw}$ generate the optimal current $I_L$ in the active shield with given impedance (Figure 2). The circuit is explained in Section 3.2. The inner objective function ends by associating an objective value – described in Section 3.3 – to the shield studied at that time point of the optimization procedure. The termination criteria for the inner GA are the same as for the main GA.

The objective value returned by the main GA is the best objective value of the inner GA. This value corresponds with the best numbers of turns and the best $I_{gcw}$ for a fixed GCW and active shield geometry.

### 3.2 The components of the electric circuit

Once the optimal compensation current $I_L$ is known, the inner objective function has to design an electric circuit that creates the current $I_L$ in the active shield (Figure 2). Figure 4 shows in the complex plane the vector $I_L$ that has to be built using the vector $I_{gcw}$. We recall that the induced current and voltage in one turn of the GCW are fixed within the inner objective function: $I_{gcw} = I_{gcw} t_{gcw}$ is an input argument[2] and $V_{gcw} = V_{gcw}/t_{gcw}$ is found in the database of field distributions. $t_{gcw}$ is the number of turns of the GCW.

The voltage $V_L$ needed to generate $I_L$:

$$V_L = \sum_{k=1}^{N} \left( V_{L,k} + R_{L,k} i_k + j \omega L_{L,k} i_k^2 \right)$$

(1)

is found using the numbers of turns $t_k$, the resistance $R_{L,k}$, the inductance $L_{L,k}$ and the induced voltage $V_{L,k}$ in coil $k$. The last three values are stored in the memory by

![Figure 4](image_url)

Vector plot showing the angles of the GCW current and voltage that have to be transformed into the load voltage and current by the electric circuit.

**Note:** The excitation current is the phase reference, chosen along the horizontal axis. The amplitudes are not on scale.
previous FE calculations (Section 3.1). Notice that in equation (1) some approximations are made: all mutual inductances between two compensation coils and between a compensation coil and the GCW are neglected; $V'_{L,k}$ is the voltage induced in coil $k$ only due to the excitation coil; $L_{\text{self},k}$ is the self inductance per turn of coil $k$ instead of the stray inductance.

Now the outputs $V_L$ and $I_L$ of the circuit are known, as well as its inputs $V_{\text{gcw}} = V'_{\text{gcw}}/t_{\text{gcw}}$ and $I_{\text{gcw}} = I'_{\text{gcw}}/t_{\text{gcw}}$ – except for the number of turns of the GCW $t_{\text{gcw}}$. Consequently, the circuit can be designed in several steps.

1. The angle $\beta$ between $I_L$ and the available (and given) $I_{\text{gcw}}$ is determined (Figure 4). If $|\beta| > 90^\circ$, then $I_L$ is replaced by its opposite. For the new $I_L$, it is now certain that $-90^\circ \leq \beta \leq 90^\circ$. Depending on the sign of $\beta$, the phase shift $\beta$ can be realized by choosing either circuit (a) or (b) in Figure 5.

2. The capacitor $C$ in Figure 5(a) or the inductance $L$ in Figure 5(b) is calculated so that $|I_L| = |I_{LC}|$. If the correct angle cannot be found with any inductance $L$, a series capacitor $C_L$ is added so that the load becomes resistive for the excitation frequency (series resonance).

3. The number of turns for the GCW is found by expressing that the available voltage from the GCW must be larger than the load voltage: $t_{\text{gcw}} V'_{\text{gcw}} - \left(t_{\text{gcw}} R'_{\text{gcw}} + i t_{\text{gcw}} X'_{\text{gcw}}\right) I'_{\text{gcw}} \geq |V_L|$. After the choice of $t_{\text{gcw}}$, the series impedance $R_{\text{ser}} + i X_{\text{ser}}$ is calculated so that the voltages match. If no $t_{\text{gcw}}$ can be found smaller than its maximal value, so that $R_{\text{ser}} > 0$, then it is

![Figure 5. Electric circuits to be inserted between the GCW and the active shield](image)

**Notes:** (a) Circuit for $\beta < 0$ (corresponding with Fig.4) and (b) Circuit for $\beta > 0$
assumed that the GCW has not enough power to drive the active shield. The objective value is then very high.

(4) The test $|\text{Re}(S_{\text{gcw}})| = |\text{Re}(V_{\text{gcw}} \cdot I_{\text{gcw}})| > |\text{Re}(S_{L})| = |\text{Re}(V_{L} \cdot I_{L})|$ checks if the GCW has enough active power.

(5) The parallel impedance $R_{\text{par}} + iX_{\text{par}}$ is a bypass for the current $I_{\text{gcw}} - I_{\text{LC}}$ that is not needed for the active shield.

### 3.3 The inner objective value

The objective value is the sum of seven penalization terms:

$$\text{ObjVal} = w_{1} \int_{S_{T\text{A}}} \frac{|B|}{S_{T\text{A}}} \, \text{d}r \, \text{d}z + w_{2} |S_{A}| + w_{3} \frac{P_{W_{\text{p,noSh}}} - P_{W_{\text{p,Sh}}}}{P_{W_{\text{p,noSh}}}} + w_{4} C_{\text{RLC}}$$

$$+ w_{5} C_{\text{Power}} + w_{6} \left( \frac{|\text{Re}(S_{\text{gcw}})|}{|\text{Re}(S_{L})|} - 1 \right) - w_{7} C_{\text{ZeroTurn}}$$

with corresponding weighting factors $w_{l}, l = 1, \ldots, 7$. The $i$th penalization term explained in the following list corresponds with the $i$th weighting factor.

1. The average norm of the magnetic flux density in the target area is the integral of $|B|$ divided by the surface of the target area $S_{T\text{A}}$ in the axisymmetric space.

2. The active and reactive power in the active shield determine the exploitation and investment costs.

3. The influence of the shields on the heating process. $P_{W_{\text{p,noSh}}}$ is the induced power in the workpiece without active shield and GCW. $P_{W_{\text{p,Sh}}}$ is the energy dissipation in the workpiece with GCW and active shield present. The second and the third term inhibit the GA to choose a large GCW very close to the excitation coil.

4. A coefficient penalizing the investment costs of all resistances, inductances and capacitances in the circuit is necessary to avoid the choice of unrealistic components. This coefficient includes the number of turns of GCW.

5. A Boolean with very high weighting factor $w_{5}$. If the GCW produces enough power for the active shield, this term is zero. Otherwise, it overrules all other terms, making it sure that this solution is rejected by the inner GA.

6. If the GCW produces much more power than the active shield needs, a lot of energy is wasted. The penalization term is small if both powers have a similar magnitude.

7. $C_{\text{ZeroTurn}}$ is the number of coils with zero turns. A coil with zero turns need not be built. This factor is negative, to encourage an easy to build active shield with few compensation coils.

#### 4. Numerical model for the environment of the induction heater

To study the magnetic stray field of induction heaters, a FE model is developed (Silvester and Ferrari, 1990). The linear model is axisymmetric, quasi-static and time-harmonic and it models the heating device together with GCW and compensation coils. Figure 6 shows the geometry, defined by one or more workpieces and excitation...
coils, one GCW, a number of compensation coils and the air surrounding the induction heater. Due to symmetry with respect to $z = 0$, only the properties in the space $z > 0$ are shown.

The modelled induction heater consists of a one turn excitation coil and an aluminium workpiece to be treated thermally. Their dimensions and properties can be found in Table I. This layout was chosen as it corresponds to the experimental set-up of an induction heater for the thermal treatment of wheels. A 1 m long and 0.8 m high rectangle symbolizes the target area where the operator is working and where the average magnetic induction $B$ should be minimized. Above the target area, a number of compensation coils can be found in Figure 6. These coils should minimize the magnetic induction in the target area. However, very high compensation currents are needed to reduce $B$ in the lower left corner of the target area: the maximum value of $B$ will occur in this corner – the region closest to the excitation coil – and the active compensation coils are further away of this area than the excitation coil. Thus, one extra

![Figure 6. Finite-element layout, scales in metre (FEM: magnetic vector potential $\vec{A} = A_\phi \vec{I}_\phi$)](image)

<table>
<thead>
<tr>
<th>Property</th>
<th>Outer radius (m)</th>
<th>Thickness (mm)</th>
<th>Height (mm)</th>
<th>$\sigma$ ($\Omega$/m)</th>
<th>$\mu \times \mu_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excitation coil</td>
<td>0.2027</td>
<td>1.50</td>
<td>16.0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Workpiece</td>
<td>0.1910</td>
<td>–</td>
<td>10.0</td>
<td>$3.7 \times 10^7$</td>
<td>1</td>
</tr>
<tr>
<td>Steel pass. Shield</td>
<td>0.3065</td>
<td>0.65</td>
<td>190</td>
<td>$5.9 \times 10^6$</td>
<td>372</td>
</tr>
<tr>
<td>Copper pas. Shield</td>
<td>0.3050</td>
<td>0.50</td>
<td>190</td>
<td>$5.2 \times 10^7$</td>
<td>1</td>
</tr>
</tbody>
</table>

**Notes:** Geometrical and electromagnetic properties of the excitation coil, the workpiece and two classical passive shields. In the excitation coil, 40 A current is forced; $\sigma = 0$ means that no skin effect is taken into account. Dimension of radius and thickness are along the $r$-axis; dimension of height is along the $z$-axis.

Table I.
compensation coil and the GCW have been added, at radius between 0.23 and 0.45 m to reduce the field in the lower left corner of the target area. The GCW and the neighbouring extra compensation coil N increase the efficiency of the other N − 1 compensation coils. In the numerical field calculation, the known current density in the excitation coil and in the compensation coils is denoted by \( \vec{J}_e = J_e(r,z) \vec{1}_\phi \). In the domain \( \Omega \), the magnetic induction is written as \( \vec{B} = \nabla \times \vec{A} \), with the vector potential \( \vec{A} = A_\phi(r,z) \vec{1}_\phi \). It is well known from Maxwell equations that \( A_\phi(r,z) \) obeys a second-order boundary value problem (BVP) in \( \Omega \), i.e.

\[
\frac{1}{\mu} \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial}{\partial r} (rA_\phi) \right) + \frac{1}{\mu} \frac{\partial}{\partial z} \left( \frac{\partial}{\partial z} (rA_\phi) \right) - i\sigma \omega A_\phi = -\vec{J}_e \quad (3)
\]

together with the boundary condition (BC) (Figure 6),

\[
A_\phi = 0 \quad \text{on } \Gamma_1 \quad (4)
\]

Here \( \mu \) and \( \sigma \) are the permeability and the electric conductivity of the material present in \( \Omega \). \( f = \omega/2\pi \) is the frequency of the source term \( J_e \). The BC on \( \Gamma_1 \) describes magnetic isolation.

5. Simulation results

The excitation current necessary to heat the workpiece quickly is 4,000 A or more. As the experimental test set-up works with reduced power, the current is 100 times reduced in the simulations. For the excitation current, a sinusoidal excitation current as high as 40 A at 1 kHz is used in the simulation. Consequently, to obtain realistic values, the flux densities, voltages and currents displayed further in this paper should be multiplied by 100, and the powers by \( 10^4 \).

In Sections 5.1 and 5.2, the shielding effectiveness of a classical passive shield, respectively, a GCW are discussed both in combination with an active shield. This makes it possible to find the advantages and disadvantages of the GCW, compared to the classical passive shield. Also the losses in the shields and the influence on the heating process are studied.

To be able to evaluate the field reduction of the shields, some reference values of the unshielded induction heater are given in Table II. Without any passive or active shield, the average value of \( B \) in the target area is 289 nT. The maximum value of 1.965 \( \mu \)T is found in the lower left corner of the target area. The energy dissipation in the

| Shields | Passive or GCW | \( B_{\text{avg}} \) (nT) | \( B_{\text{max}} \) (nT) | \( P_{\text{wp}} \) (mW) | \( P_p \) (mW) | \( P_a \) (mW) | \( w_1 \) | \( w_2 \) | \( w_3 \) | \( w_4 \) | \( w_5 \) | \( w_6 \) | \( w_7 \) |
|---------|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| None    | No            | 289             | 1965            | 197             | –               | –               | 10^9            | 0               | 0               | 0               | –               | –               |
| Pas., Fe| No            | 95.9            | 551             | 189             | 26.7            | –               | 10^9            | 0               | 0               | 0               | –               | –               |
| Pas., Fe| Yes           | 29.9            | 409             | 189             | 26.7            | –               | 10^9            | 3               | 5               | 10              | –               | –               |
| Pas., Cu| No            | 40.3            | 216             | 178             | 8.15            | –               | 10^9            | 0               | 0               | 0               | –               | –               |
| Pas., Cu| Yes           | 5.32            | 95.7            | 163             | 16.9            | 0.82            | 10^9            | 0.05            | 5               | 30              | –               | –               |
| GCW1    | Yes           | 6.36            | 27.1            | 163             | 36.3            | (28.1)          | 10^9            | 1               | 1               | 0.1             | 500             | 2               |
| GCW2    | Yes           | 27.7            | 497             | 189             | 7.1             | (5.9)           | 10^9            | 2000            | 100             | 1               | 500             | 20              |
| GCW3    | Yes           | 13.3            | 151             | 180             | 24.7            | (21.4)          | 10^9            | 100             | 100             | 1               | 500             | 20              |

Table II. For several shielding situations: average and maximal \( B \) in the target area, induced heating in the workpiece \( P_{wp} \), in the passive shield or the GCW \( P_p \) and in the active shield \( P_a \), weighting factors in (2)
workpiece $P_{wp}$ is determined by integrating the energy dissipation of the induced eddy currents over the volume of the disc:

$$P_{wp} = 2\pi \int_S \frac{J^2}{\sigma} r \, dr \, dz, \quad \text{with } J = -i\sigma \omega A_\phi$$

with 40 A current (frequency 1 kHz) in the one turn-excitation coil, $P_{wp}$ is 197 mW.

5.1 Passive shield and active shield
We consider the induction heater with only a passive shield in copper or steel. The position, the height, and the electromagnetic properties of the shield strongly influence the field reduction and the electromagnetic losses in the shield. Table II shows the average of the absolute values of the flux density (average induction norm) in the target area and the induced heating in the workpiece and in the passive shield for both the steel and the copper shield with geometry and material properties shown in Table I. The excitation frequency is 1 kHz and the excitation current is 40 A. Copper seems to cause lower B-levels in the target area and lower energy dissipation in the passive shield than steel, but has more influence on the heating process.

Table II mentions shielding results for a globally optimized active and passive shield: the compensation coil positions as well as the height and radius of the passive shield are optimized and can be found in Sergeant et al. (2003). The active shield consists of twice nine compensation coils. The coil positions are constrained as not all coil positions are convenient, due to the needed accessibility of the workpiece.

The field reduction is high, especially for the copper shield. Also the losses in the copper shield are acceptable: 16.9 mW. They are extremely low in the corresponding active shield (0.819 mW) due to the low compensation current. With 17 per cent heat reduction however, the influence on the heating process is much higher than for the steel passive shield.

5.2 GCW and active shield
The active shield consists of only five compensation coils of which the fifth is placed close to the GCW. Coils 1-4 have a radius in the range 0.210-1.45 m and are subject to inequality constraints: coil $k$ must have a radial position that is at least 40 mm higher than coil $k-1$. Coils 2-4 have a fixed $z$-coordinate ($z = 1.15$ m) and an optimized $r$ coordinate, while coils 1 and 5 have both their $r$ and $z$ coordinates optimized. The GCW can be placed between 0.23 m radius and compensation coil 5 (with a maximum of 0.33 m). Its height can be 10, 30, or 80 mm. Thus, the total number of variables to be optimized is nine. The population in the main GA consists of 150 individuals with 9 discrete variables each, separated in 5 subpopulations. The inequality constraints for the coil positions are implemented by assigning a high objective value to an individual that violates a constraint. For this individual, the FE calculations and the inner GA are skipped to save CPU time. For one total optimization, the GA calculated 24 generations (GCW1) to 27 generations (GCW2).

In Table II, three optimizations with different weighting factors in the objective function illustrate how the optimal solution depends on these weighting factors. The coil positions and the optimal compensation and GCW current can be found in Table III. In the first optimization, all weighting factors were low except the first one (and the fifth that must always be high as explained in Section 3.3). The result is an active
shield that realizes the maximal reduction (33 dB) of the average flux density in the
target area. Nevertheless, this solution is not acceptable because the power
consumption of the GCW $P_p$ is very high: 25 per cent of the power induced in the
workpiece. Moreover, the GCW and active shield influence the heating process too
much, as the workpiece power $P_{wp}$ is much lower than in the unshielded induction
heater. The power in the active shield $P_a$ is put between brackets in Table II as it is
already taken into account when considering the power $P_p$ in the GCW: the total
dissipation in the shield is $P_p$ and not $P_a + P_p$ like for the classical passive and active
shield. In spite of the very low $|B_{avg}|$, the optimization GCW1 shows that a good choice
of the weighting factors is essential to achieve a suitable solution.

The second combined GCW and active shield is obtained with $w_1$ identical to its
value in GCW1. $w_3$, $w_4$ and $w_5$ have “normal” values and $w_2$ is exceptionally high: a
high penalization of the exploitation cost favours a GCW with an economical power
consumption. Table II indicates indeed that the power consumption in the GCW $P_p$ is
only 7.1 mW. Of course, the remaining average flux density is higher than for GCW1:
27.7 nT. With a field reduction of 20 dB however, the shield is still effective. The
consequence of the low $P_p$ is that the influence on the heating process is only 4 per cent,
though the corresponding weighting factor $w_3$ was not high. That $P_a$ has the same
magnitude as $P_p$ is due to the factor $w_6$, that inhibits “wasted” power. Notice that the
need for low power dissipation in the shield convinced the GA to choose the GCW at a
position rather far from the excitation coil (at radius 0.31 m). At this position, the
maximally induced power in the GCW is low. It is interesting to observe that for the
considered geometry, the maximal power that can be induced in the GCW is much
higher than the power that is needed to build an efficient active shield.

For the last GCW optimization, $w_7$ was chosen equal to three. This weighting factor
$w_7$ causes a reduction of the objective value when a coil has zero turns. This means that
the number of compensation coils is the least possible: the optimal shield in
optimization GCW3 has only one compensation coil, close to the GCW. The remaining
average magnetic flux density in the target area is 13.3 nT (27 dB reduction), which is
in between GCW1 and GCW2. The 8.4 per cent heat reduction in the workpiece is
acceptable. The induced power in the GCW $P_p$ is similar to $P_p$ for a classical steel
passive shield and higher than in a classical copper passive shield. However, it is
recalled that this power is not dissipated like in the passive shield. Eighty seven per cent
of this power is provided to the active shield; the rest is dissipated in the GCW and the
electric circuit. The objective value (2) was 39.00, consisting of 7 terms: 13.28 (1. $|B_{avg}|$);

<table>
<thead>
<tr>
<th>Shield</th>
<th>GCW1</th>
<th>GCW2</th>
<th>GCW3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{gcw}$</td>
<td>$-479 - 33.2i$ mA</td>
<td>$-22.8 - 7.2i$ mA</td>
<td>$-57.7 - 48.9i$ mA</td>
</tr>
<tr>
<td>$I_{z}$</td>
<td>$-108.8 + 19.5i$ mA</td>
<td>$-32.6 + 6.3i$ mA</td>
<td>$-131.3 + 19.7i$ mA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coil</th>
<th>$r_i$ (m)</th>
<th>$z_i$ (m)</th>
<th>$t_i$</th>
<th>$r_i$ (m)</th>
<th>$z_i$ (m)</th>
<th>$t_i$</th>
<th>$r_i$ (m)</th>
<th>$z_i$ (m)</th>
<th>$t_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCW</td>
<td>0.230</td>
<td>0.030</td>
<td>34</td>
<td>0.310</td>
<td>0.010</td>
<td>49</td>
<td>0.230</td>
<td>0.030</td>
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</tr>
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<td>1</td>
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<td>-1</td>
<td>0.340</td>
<td>0.950</td>
<td>-10</td>
<td>0.250</td>
<td>0.710</td>
<td>0</td>
</tr>
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<td>2</td>
<td>0.260</td>
<td>1.150</td>
<td>-1</td>
<td>0.730</td>
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<td>-2</td>
<td>0.310</td>
<td>1.150</td>
<td>0</td>
</tr>
<tr>
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<td>0</td>
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<td>3</td>
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<td>1.150</td>
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<td>1.150</td>
<td>0</td>
<td>1.250</td>
<td>1.150</td>
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<tr>
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<td>0.060</td>
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<td>0.090</td>
<td>36</td>
<td>0.330</td>
<td>0.080</td>
<td>20</td>
</tr>
</tbody>
</table>

Table III. For the three optimizations with GCW: optimal compensation current, GCW and compensation coil positions and numbers of coil turns.
4.14 (2. Exploitation cost); 8.44 (3. Influence on heating); 21.08 (4. Circuit components); 0 (5. Enough power); 4.06 (6. Wasted power); −12 (7. Zero turn coils). A low average field is caused by the rather high first factor. The exploitation cost and the influence on the heating process are moderate, and so are the corresponding costs. The high value of the circuit components is mainly due to the rather high capacitance of 26.2 μF. Due to the sixth cost, \( P_a \) has the same magnitude as \( P_p \). Finally, the high negative value of the zero turn coils explains why the optimal shield has only one compensation coil. Figure 7 shows the field distribution for GCW3.

For the shielding situations with GCW, we can conclude that the performance is similar to the classical passive and active shield situations. Nevertheless, the latter have more compensation coils at higher distance from the induction heater and they need an external controller and power supply.

6. Experimental evaluation of the numerical model
To evaluate the numerical model, simulation results were compared with the measurements on an experimental set-up of an induction heater with the same geometry (Figure 6 and 7) and properties (Table I) as used in the simulations in the previous section. The GCW and the compensation coils were positioned as shown in Table III for GCW3. Instead of 2 x 5 compensation coils – nine coils above the symmetry plane \( z = 0 \) and nine below the plane – only two compensation coils are placed close to the GCW, as the others have 0 turns. The test set-up of the shielded induction heater is at real scale: the total height of the shielded induction heater is 2.3 m and the diameter is 3 m. As mentioned earlier, the sinusoidal excitation current is reduced by a factor 100–40 A at 1 kHz. In the experimental set-up, the PC based data acquisition system samples the current in the excitation coil at 100 samples per period. The magnetic induction is measured by a 3D probe with sensitivity 1 V/10 μT and frequency range from 50 Hz to 100 kHz. The probe is a 3D version of the loop antenna in Sergeant and Van den Bossche (2002), but with small coils of 40 mm diameter instead of 250 mm. To avoid disturbance of the measurements by ambient

![Magnetic induction in nT for GCW3](image_url)

**Figure 7.** Magnetic flux density in nT for GCW3
fields (mainly 50 Hz), 1,000 excitation periods are measured and a Fourier analysis is executed.

Figure 8 compares the measurements on the induction heater test set-up with the numerical results by showing the flux density in the $z = 0$ plane for GCW3. Three flux density curves from Sergeant et al. (2003) are added as reference: the unshielded heater, the heater with passive shield and the heater with passive and active shield. The correlation between the measured and the simulated flux density of GCW3 is good, given the high sensitivity of the resonant circuit to tuning. The curves have the same course, and the reduction of $B$ is similar. Figure 8 shows that GCW3 reduces the field effectively in spite of its low number of coils. The calculated values of the components in the circuit, as well as load and GCW currents, voltages and powers, are compared with the experimental ones used in Table IV.

Table IV. Calculated and experimental values for GCW3: the components in the passive network; voltage, current and power in the GCW and in the active shield load at 1 kHz.
7. Dynamic behaviour of the shield

7.1 The workpiece temperature

During the heating of the aluminium workpiece, the temperature increases gradually from 20°C to a maximum which is chosen to be 1,000°C. Due to the temperature rise, the conductivity of the workpiece decreases from $3.7 \times 10^7$ to $7.1 \times 10^6/\Omega \cdot m$. Consequently, the magnetic stray field changes and also the induced voltage in the GCW and the compensation current are gradually altered.

Figure 9 shows the simulated $|B_{avg}|$ in the target area as a function of the workpiece temperature. The dash-dot line in Figure 9 is obtained by assuming that the compensation and GCW currents don’t change. This is the case with an “excitation current transformer”: a current transformer with a conductor of the excitation current as primary winding, and the GCW as secondary winding. With both excitation and compensation current having constant amplitude, the average magnetic flux density in the target area increases almost 4 times. With the “stray flux transformer” GCW3 (solid line in Figure 9), $|B_{avg}|$ hardly rises from 13.3 nT at 20°C to 14.3 nT at 1,000°C, because also $|I_{gcw}|$ increases from 0.133 to 0.153 A. Although it is difficult to see in Figure 9, $B_{avg}$ is not minimal at 0°C, but at 20°C – the temperature for which the optimization was executed.

7.2 A workpiece with different size

If the aluminium workpiece with 191 mm radius is replaced by another workpiece –, e.g. an aluminium workpiece with the same thickness, but 150 mm radius – the magnetic stray field around the induction heater increases. Figure 10 shows the measured magnetic flux density in the $z = 0$ plane, again for GCW3. With $I_{gcw}$ and $I_{L,0}$ constant, $|B_{avg}|$ is high in the target area. $I_{L,0}$ is equal to $0.133 \times 10^{17} A$: the calculated value. With both $I_{gcw}$ and $I_L$ determined by the GCW, the flux density is lower. The presented type of shield seems to be able to “control” the compensation current.
7.3 The excitation frequency

Measurements on the set-up of GCW3 are done for other frequencies than 1 kHz, without altering the GCW and active shield layout. Figure 11 shows that even a small variation in frequency deteriorates the shielding performance. This is due to the second-order resonant circuit, of which the phase characteristic is steep near the

**Notes:** Dotted line with fixed calculated compensation current $I_{L0} = 133 \cdot e^{171^\circ} mA$ and solid line with compensation current chosen by the GCW: $236 \cdot e^{178^\circ} mA$

![Graph showing flux density vs. radius](image1)

**Figure 10.** Measured flux density with a smaller aluminium disc (150 mm instead of 191 mm) in the $z=0$ plane at 1 kHz.

![Graph showing frequency characteristic](image2)

**Figure 11.** Measured frequency characteristic of the GCW and active shield in two sensor positions.

**Notes:** The minimum at 1 kHz corresponds with the curve “GCW3, measured” in Fig. 8.
resonance frequency. This type of shielding is not suitable for induction heaters with changing excitation frequency.

8. Conclusion
The aim of the generating winding and the active shield is to reduce the magnetic stray field of an induction heater. The paper explains how the GA and the objective function with FE models are used to find the optimal shield design. Advantages and disadvantages of this type of shielding compared to classical active and passive shielding are:

(1) + a high field reduction and rather low energy dissipation in the shields if the weighting factors in the objective function are well chosen;
(2) + cheap and easy construction that doesn’t need a convertor, amplifier or external power supply;
(3) + the ability to adapt the compensation current and to keep the field reduction effective if the stray field changes due to changing workpiece temperature or changing workpiece size;
(4) − due to the resonant electric circuit, the shield works well only for the frequency it is designed for; and
(5) − the shielding efficiency is very sensitive to tuning of the components in the circuit.

Three optimization examples are mentioned in the paper of which one was experimentally verified. The correspondence between the measurements and the simulations is good.

Notes
1. By saving field distributions, the CPU time is reduced: a field distribution is not calculated if it is found in the memory. Saving field distributions is only useful to reduce the CPU time if the number of possible coil positions is limited. Therefore, the GA optimizes discrete variables i.e. the coils are given discrete positions.
2. The prime refers to the properties when only 1 turn in the GCW is present.
3. The GCW is a distributed winding to show the analogy with a classical passive shield. The GCW would work as well if it is modelled by two stranded conductors like the other compensation coils.

References


