Local magnetic measurements in magnetic circuits with highly non-uniform electromagnetic fields

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Local magnetic measurements in magnetic circuits with highly non-uniform electromagnetic fields

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Abstract
In this paper, local magnetic measurements are carried out in magnetic circuits with non-uniform electromagnetic field patterns, including excitation windings and/or air gaps, as in the case of rotating electrical machines. The effects of sensor choice, sensor noise sensitivity and electromagnetic field inhomogeneity on the accuracy of the identification of the magnetic material properties are investigated. Moreover, the validity of the local magnetic measurements is confirmed by numerical models, based on the finite element method. The paper comprehensively discusses the possibilities, difficulties and limitations of local magnetic measurements in magnetic circuits with non-uniform electromagnetic fields. It is shown that higher accuracy is obtained when the measurements are performed in regions with less stray fields.

Keywords: magnetic measurements, magnetic sensors, non-uniform field patterns

(Some figures in this article are in colour only in the electronic version)

1. Introduction
Magnetic measurements are indispensable for the identification of magnetic properties of materials. Specifically, local magnetic measurements have gained a lot of interest during the last decade, since they are becoming important tools in different research topics. Indeed, in [1–4] the influence of mechanical deformation on the magnetic properties of electrical steels, by the aid of local magnetic measurements, has been studied. The effect of different cutting techniques on electrical steel properties has been analyzed in [5]. The structure of a grain-oriented electrical steel and its anisotropic behavior have been investigated and reported in [6–8], using local magnetic measurements. The single-valued characteristics and the hysteresis loops of an electrical steel are reconstructed, by means of local magnetic measurements, in [9, 10].

In all previously mentioned references, the local magnetic measurements were carried out on a simple geometry of a magnetic material where the magnetic field patterns are nearly uniform. However, local magnetic measurements in magnetic circuits with highly non-uniform magnetic field patterns have not been investigated to full extent, up to now.

Moreover, it is difficult to reconstruct the magnetic material properties ‘B–H curve’ in more complex geometries with a high degree of field non-uniformity, e.g. rotating electrical machines, only based on local magnetic measurements [11]. Alternatively, these local magnetic measurements can be coupled with a numerical inverse approach in order to determine the magnetic material properties. This is surely needed when dealing with much more complex magnetic circuit geometries. Recently, a coupled experimental–numerical inverse approach has been formulated in order to characterize the magnetic material of an electromagnetic device [11, 12]. This inverse approach is needed in case no local ‘B’ and ‘H’ measurement can be done simultaneously at the same place. The input of this inverse approach is the magnetic measurements, while the output is the magnetic material properties. It has been observed that the...
accuracy of the recovered material characteristics appreciably depends on the input nature of the inverse problem, namely the ‘local magnetic measurements’.

Generally, the inverse problem is an ill-posed problem, i.e. a small error in the input data ‘measured quantities’ leads to a considerable error in the output data ‘recovered material parameters’. Consequently, the local magnetic measurements have to be accurate, reliable, stable and repeatable.

The research presented in this paper aims at analyzing the local magnetic measurements, which are the cornerstone in the inverse problem process for circuits with highly non-uniform electromagnetic field patterns, like rotating electrical machines. This aim is achieved by presenting a comprehensive comparison among different sensors to measure local magnetic quantities in such geometries. Moreover, the possibilities, difficulties and limitations of each sensor are illustrated. Furthermore, the effects of sensor choice, sensor noise sensitivity and electromagnetic field inhomogeneity on the accuracy of the identification of the magnetic material properties are investigated.

The local magnetic field strength ‘$H_{local}$’ is measured using the following different sensors: flat $H$-coil, fluxgate, Rogowski coil and Hall-probe sensors. The local magnetic induction ‘$B_{local}$’ is measured using needle probe and search coil methods [13]. The presented local magnetic measurements are numerically validated using the finite element method.

The studied geometries are described in section 2. A brief description of each magnetic sensor, used in this study, is presented in section 3. The numerical validation of the magnetic measurements based on the finite element method is shown in section 4. The results are presented and discussed in section 5. Finally, the conclusions are drawn in section 6.

2. The studied geometries

Figure 1 shows the two studied geometries, made from the same material, i.e. non-oriented electrical steel (M 700/50 A). The studied magnetic circuits are magnetic ring cores with $D_i$ and $D_o$ the inner and outer diameter respectively. Each magnetic circuit consists of ten laminations with a total thickness of 5 mm.

The excitation winding is wound over an excitation angle ‘$\theta$’ for both geometries, $G_1$ and $G_2$. In $G_2$, an air gap of 1 mm is introduced. $G_2$ is a simplified magnetic circuit for rotating electrical machines, which have a partially excited stator, and an air gap between the stator and the rotor.

Due to the symmetry in the studied geometries, the local magnetic measurements were carried out at the indicated positions in figure 1. Positions 1, 2 and 3 are located at $\phi = 0$, $\phi/4$ and $\phi/2$, respectively, where $\phi$ is the unwound angle in degree ($\phi = 360° - \theta'$).

These positions have been chosen in the unwound area, and not in the wound area, in order to simulate the availability of the local magnetic measurements in rotating electrical machines. It is possible to measure locally magnetic quantities in the unwound area of rotating electrical machines, but not in the wound area because the magnetic material is not accessible.

3. Magnetic sensors

The theoretical background and the specifications of each magnetic sensor, used in this study, are briefly discussed in this section. All mentioned characteristics are mainly provided by the manufacturer and/or calibrated by a Helmholtz coil at our laboratory.

3.1. Local magnetic field measurements

3.1.1. Double flat $H$-coils. The flat $H$-coil sensor is an induction sensor, which measures the tangential field component directly above the sample. Its operation is based on the fact that the magnetic field at the material surface (inside the magnetic material) is the same as the tangential field component directly above the sample. We use the double flat $H$-coil sensor, where the magnetic field at the sample surface can be extrapolated from the two output signals [14].

The used double flat $H$-coils have a thickness of 1.5 mm, and the cross-sectional area equals 15.7 mm$^2$ each. Each $H$-coil contains a 500 turn wire of 0.1 mm diameter (five layers).
3.1.3. Rogowski coil. The Rogowski coil, or the Chattock sample, as shown in figure 2(a), is a special kind of helical coil sensor uniformly wound on a relatively long non-magnetic, flexible strip, bent in such a way that its endfaces are placed in close contact with the sample surface. Here, the used Rogowski coil has 1308 turns, with a sensitivity of 1.79 nV/(A m$^{-1}$). The dimensions of the Rogowski coil are shown in figure 2(c).

3.1.4. Hall-probe sensor. Hall-probe sensors are based on the appearance of a potential difference ‘Hall voltage’, transverse to an electric current in the conductor and a magnetic field perpendicular to that current. In this study an array of four vertical commercial Hall-probe elements (Allegro A1321ELHLT-T) positioned at 1.7, 3.12, 5.05 and 6.22 mm above the specimen, with a sensitivity of 62.8 $\mu$V/(A m$^{-1}$), is used. The surface area of the active element of the Hall-probe sensor is about 0.7 $\times$ 0.5 mm$^2$ [18]. Also, the surface sample fields are obtained using the extrapolation method. The schematic diagram of the Hall-probe sensor is shown in figure 2(d).

3.2. Local magnetic induction measurements

3.2.1. Search coil method. The search coil method is a well-known conventional way for measuring the local magnetic induction in magnetic circuits. The induced voltage over the wound coil ($V$) is proportional to the magnetic induction: $B(t) = \frac{1}{\mu n} \int V \, dt$, where $n$ and $S$ are the number of turns and the cross section of the coil respectively. In order to reduce the error due to stray fields, the lead wires of the search coil are twisted [19].

Although the search coil method is a ‘master’ technique for measuring the magnetic induction, it is not preferable when dealing with local magnetic induction measurements because it is a destructive technique. It requires drilling holes which introduces stress altering the magnetic properties locally [20]. In this paper, in order to avoid any modification in the magnetic properties, we use the search coil method to measure a quasi-local magnetic induction. A quasi-local measurement means measuring a magnetic induction at a specific region around the total thickness of the magnetic circuit, as shown in figure 1.

We performed the quasi-local magnetic induction measurements in the objects, using the search coil method, in two different regions, see figure 1. A concentrated search coil with $n_1 = 200$ is placed inside the excitation coil, in order to quantify the stray fields in each geometry. Additionally, a movable search coil ($n_2 = 150$) is free to move in the unwound area, in order to validate experimentally the ‘real’ local $B$-measurements using the needle probe method. This approximation will be discussed in detail in section 5.4.

3.2.2. Needle probe method (NPM). The needle probe method is based on the fact that when a time-dependent flux $\Phi$ is enforced in a steel sheet, eddy currents ($J = \sigma E$) are
for the air flux. Two extra needles are used to compensate the basic two needles’ needle probe, which consists of four needles; the output signal is sensitive to noise interference [21, 22].

Due to the error introduced by the non-homogeneous air fields, the authors have presented a modified needle probe method [11], based on an anti-series connection of two sets of fields, the air fluxes as well (\(V_{12} \sim B_{\text{material}} + B_{\text{air}}\)). The extra two needles should be located as close as possible to the basic needles, and it should be short-circuited directly above the sample surface. Note that needles 3 and 4 do not make contact with the material. So, the output signal of the extra two needles \(V_y\) is approximately proportional to the stray fields only \(V_{12} \sim B_{\text{air}}\). Due to the anti-series connection, the air fluxes have been eliminated from the output signal \(V_{\text{total}} = V_{12} - V_{34} \sim B_{\text{material}}\).

3.3. Comparison between the magnetic sensors

Tables 1 and 2 show a brief comparison between the previously mentioned sensors in magnetic field and magnetic induction measurements, respectively.

For magnetic field sensors (table 1) each sensor has advantages and disadvantages due to the differences among their characteristics. We can divide the sensors into two groups: self-made sensors (flat \(H\)-coil and Rogowski coil) and commercial sensors (fluxgate and Hall-probe sensors).

The main advantage of the self-made sensors is their availability. These sensors can be fabricated, easily and cheaply, at any laboratory. Also, these sensors do not require any supply voltage to work. However, the output voltages of these sensors, which are proportional to the time derivative of the measured magnetic field strength, are too weak especially at low frequencies. So, extra components for signal conditioning are needed, such as amplification, filtering and integration units. These extra components complicate the measurement set-up, and hence introduce an error in the measurements.

On the other hand, the output voltage of the commercial sensors is directly proportional to the measured magnetic field strength. So, no extra components for signal conditioning are needed, which simplify the measurement set-up. However, these sensors require a separate supply voltage for their excitation.

For magnetic induction sensors (table 2) it is clear that the search coil method is much better than the NPM: it needs less measurement set-up components. However, as discussed before, the NPM is preferable for local measurements as it is a ‘non-destructive method’.

4. Measurement validation using numerical techniques

In order to verify the magnetic measurements, numerical models are constructed based on the finite element method (FEM). The numerical method is chosen as a validation tool rather than the analytical method in order to simulate the stray fields and the fringing effects in the most accurate way. Although the numerical models may contain modeling errors, it is assumed that these numerical models are accurate enough to be a ‘golden standard’ for the validation of the measurements.

### Table 1. Comparison among different sensors for local magnetic field measurements.

<table>
<thead>
<tr>
<th></th>
<th>Flat (H)-coil</th>
<th>Fluxgate sensor</th>
<th>Rogowski coil</th>
<th>Hall-probe sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage</td>
<td>(\propto \frac{2\text{flux}}{\text{air}})</td>
<td>(\propto H_{\text{measured}})</td>
<td>(\propto H_{\text{measured}})</td>
<td>(\propto H_{\text{measured}})</td>
</tr>
<tr>
<td>Weak signal</td>
<td>Strong signal</td>
<td>No integration</td>
<td>No integration</td>
<td>Strong signal</td>
</tr>
<tr>
<td>Requires integration</td>
<td>No amplification</td>
<td>No integration</td>
<td>No integration</td>
<td>No integration</td>
</tr>
<tr>
<td>Requires amplification</td>
<td>No filtering</td>
<td>No integration</td>
<td>No integration</td>
<td>No filtering</td>
</tr>
<tr>
<td>Requires filtering</td>
<td>Requires separate supply voltage</td>
<td>No integration</td>
<td>No integration</td>
<td>Requires filtering</td>
</tr>
</tbody>
</table>

### Table 2. Comparison between two different sensors for local magnetic induction measurements.

<table>
<thead>
<tr>
<th></th>
<th>Search coil</th>
<th>Needle probe method (NPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage</td>
<td>(\propto \frac{2\text{measured}}{\text{air}})</td>
<td>(\propto \frac{B_{\text{measured}}}{\text{air}})</td>
</tr>
<tr>
<td>Strong signal</td>
<td>No number of turns</td>
<td>Too weak signal</td>
</tr>
<tr>
<td>Requires integration</td>
<td>Requires integration</td>
<td>Requires integration</td>
</tr>
<tr>
<td>Normally no amplification</td>
<td>Requires amplification</td>
<td>Requires filtering</td>
</tr>
<tr>
<td>Normally no filtering</td>
<td>Requires filtering</td>
<td>Requires filtering</td>
</tr>
</tbody>
</table>

Figure 3. The needles positioning of the proposed modified needle connection.
5. Results and discussion

The three-dimensional FEM solves the nonlinear quasi-static Maxwell’s equation: \( \nabla \times (1/\mu(A) \nabla \times A) = J \) for the unknown magnetic vector potential \( A \), and a certain given excitation current density \( J \). The nonlinear magnetic permeability \( \mu \) is known from the \( B-H \) magnetic characteristic.

The input of these numerical models is the excitation current and the nonlinear \( B-H \) normal magnetization characteristic of the material, which has been obtained from a classical ring core measurement on a fully excited, uniformly magnetized magnetic ring core. In the numerical models, hysteresis effects are not included. This is acceptable because the numerical validation of the measurements is only based on the peak values of experimental identified hysteresis loops. Here, the magnetic induction \( 'B' \) is obtained from the integrated induced voltage of the measurement winding, and the magnetic field strength \( 'H' \) is the scaling of the excitation current according to Ampère’s law.

The two geometries of figure 1 have been modeled taking into account the symmetry of the system. By imposing appropriate boundary conditions to the symmetry planes, we reduced the numerical analysis to one-fourth of the system. In this way, the computation time could be reduced considerably.

5.1. The effect of electromagnetic field inhomogeneity

Figures 4 and 5 show the measured and simulated local magnetic field strength \( 'H_{local}' \) at positions 1, 2 and 3, using the Hall-probe sensors, versus different values of the excitation current, in both geometries \( (G_1 \) and \( G_2 \)).

In figure 4, we consider the geometry \( 'G_1' \) and we mean by ‘Ampère’s law results’ the magnetic field \( H \) obtained by scaling the excitation current \( I \) according to \( H = \frac{NI}{Z} \), where \( N = 550 \) is the number of turns of the excitation winding and \( l_m \cong 314 \text{ mm} \) is the average material length. However, in figure 5, we consider the geometry \( 'G_2' \) and we do not compare the measured results with results from Ampère’s law.

Indeed, in this case the magnetic field depends on the value of the magnetic relative permeability \( \mu_r \) which is a function of the magnetic flux density \( B \). This is already clear from the simplified expression for the magnetic field in a highly ideal magnetic circuit: \( H = \frac{NI}{l_m (\mu_r (B))} \), where \( \delta \) is the air gap thickness.

It can be observed, from figure 4, that \( H_{local} \) follows Ampère’s law at low values of the excitation current. Here, in this case, the magnetic permeability \( '\mu' \) is high, and consequently the magnetic flux is approximately confined to the magnetic ring core. At high values of the excitation current, \( H_{local} \) is much less than the values obtained from Ampère’s law, where \( '\mu' \) is dropped gradually and the stray magnetic field is much higher. Moreover, a good correspondence between the simulated and the measured values is observed, in \( G_1 \), see figure 4. However, in \( G_2 \), a large deviation between the measured and simulated values is observed, especially at position 1 ‘near to the excitation winding’ and position 3 ‘near to the air gap’, see figure 5.

Figure 6 shows the comparison among different sensors with respect to the vertical variation of the local field strength. Flat \( H \)-coil, Hall-probe and fluxgate sensors use the extrapolation method; however, the Rogowski coil measures the local field value at the sample surface \( 'Z = 0' \).

It can be observed from figure 6 that the extrapolation method gives better information for the field value at the sample surface. Due to the rather big size of the flat \( H \)-coil compared to fluxgate or Hall-probe sensing elements.
results (Hall-probe sensors ‘•’, flat $H$-coil ‘□’, fluxgate ‘♦’, simulated ‘□’; the Rogowski coil measurement is shown with an error bar at ‘Z = 0’) $(D_i = 90$ mm, $D_o = 110$ mm, $\theta = 230^\circ$).

Concerning the field inhomogeneity above the sample in $G_2$, the behavior of the field inhomogeneity at position 2 is approximately similar to the behavior in $G_1$, see figure 6. However, the field behavior is dramatically changed at position 3 ‘near to the air gap’.

Figure 7 shows the magnetic field inhomogeneity above the sample at position 3, in $G_2$, using Hall-probe sensors and flat $H$-coils. The results of the fluxgate and Rogowski coil are not shown, due to the high fields which exceed the detectable range of the fluxgate sensor. Moreover, the output signal of the Rogowski coil is completely distorted due to the presence of stray fields and fringing effect.

It was expected that the field at the sample surface has the maximum value, but due to the air gap, and consequently the fringing effect, the field increases with increasing height. At a certain height value, here ‘$Z \approx 5$ mm’, the field decreases again. So the implementation of the extrapolation method has to be done in a cautious way.

Table 4 shows the measured tangential field values at ‘$Z = 0$’ and the simulated values at position 3 in $G_2$. It is obvious that the errors between the simulated and measured values using Hall-probe sensors are large.

5.2. The effect of sensor positioning

The accuracy of the magnetic measurements is highly dependent on the position of the measurements, especially at magnetic circuits with high non-uniform fields. In this section, we illustrate the effect of the sensor positioning along the radial and the circumference directions on the measurement accuracies.

5.2.1. Sensor positioning along the radial direction. In order to clarify the effect of sensor positioning along the radial direction, new dimensions with bigger core width of both geometries are used (i.e. $D_i = 95$ mm, $D_o = 145$ mm, $\theta = 230^\circ$).

Figure 8 shows the radial variation of the magnetic field strength at position 3, for different excitation currents in $G_1$. Similar results are obtained for $G_2 (\pm 5$ mm error in the sensor position along the radial direction results approximately in $\pm 50$ A m$^{-1}$ error for the magnetic field for the low excitation current 0.5 A, and $\pm 100$ A m$^{-1}$ error for the magnetic field for the high excitation current 2 A). It is also clear, from figure 8, that the error between the measured and the simulated field values is high in the proximity of the sample edge, i.e. radius = 50 or 70 mm.

Table 3. The measured and simulated field values in $G_1$, ‘position 3’.

<table>
<thead>
<tr>
<th>Excitation current (A)</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{\text{FEM}}$ (A m$^{-1}$)</td>
<td>651</td>
<td>942</td>
<td>1123</td>
<td>1270</td>
</tr>
<tr>
<td>$H_{\text{Hall}}$-probe (A m$^{-1}$)</td>
<td>665</td>
<td>958</td>
<td>1143</td>
<td>1292</td>
</tr>
<tr>
<td>$H_{\text{flat}}$-coil (A m$^{-1}$)</td>
<td>655</td>
<td>929</td>
<td>1110</td>
<td>1264</td>
</tr>
<tr>
<td>$H_{\text{fluxgate}}$ (A m$^{-1}$)</td>
<td>630</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$H_{\text{Rogowski}}$ (A m$^{-1}$)</td>
<td>595±42</td>
<td>885±55</td>
<td>1137±52</td>
<td>1295±75</td>
</tr>
<tr>
<td>$</td>
<td></td>
<td>H_{\text{FEM}} - H_{\text{Hall}} $$\text{-probe} $$</td>
<td></td>
<td>$ (A m$^{-1}$)</td>
</tr>
</tbody>
</table>

Table 4. The measured and simulated field values in $G_2$, ‘position 3’.

<table>
<thead>
<tr>
<th>Excitation current (A)</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{\text{FEM}}$ (A m$^{-1}$)</td>
<td>620</td>
<td>969</td>
<td>1070</td>
<td>1142</td>
</tr>
<tr>
<td>$H_{\text{Hall}}$-probe (A m$^{-1}$)</td>
<td>669</td>
<td>1045</td>
<td>1162</td>
<td>1235</td>
</tr>
<tr>
<td>$H_{\text{flat}}$-coil (A m$^{-1}$)</td>
<td>751</td>
<td>1162</td>
<td>1289</td>
<td>1354</td>
</tr>
<tr>
<td>$</td>
<td></td>
<td>H_{\text{FEM}} - H_{\text{Hall}} $$\text{-probe} $$</td>
<td></td>
<td>$ (A m$^{-1}$)</td>
</tr>
</tbody>
</table>
Figure 7. The magnetic field inhomogeneity above the sample at position 3, in \( G_2 \), using Hall-probe sensors and flat \( H \)-coils (\( D_i = 90 \) mm, \( D_o = 110 \) mm, \( \theta = 230^\circ \)).

Figure 8. The field strength inhomogeneity along the radial direction for different excitation currents, position 3, \( G_1 \) (extrapolated results using Hall-probe sensors ‘\( \square \’)’, simulated results ‘\( \circ \’) (\( D_i = 95 \) mm, \( D_o = 145 \) mm, \( \theta = 230^\circ \)).

5.2.2. Sensor positioning along the circumference. In order to clarify the effect of sensor positioning along the circumference, new dimensions with less excitation angle of both geometries are used, i.e. \( \theta = 130^\circ \).

Figure 9 depicts the magnetic field strength inhomogeneity along the circumference of the unwound area, in both geometries (\( G_1 \), \( G_2 \)). Extrapolated results using Hall-probe sensors (\( D_i = 95 \) mm, \( D_o = 145 \) mm, \( \theta = 130^\circ \)).

Figures 8 and 9 illustrate the sensitivity of sensor positioning, especially for magnetic circuits with air gap, on local field measurements. It is clear that small uncertainty in the sensor position along the circumference results approximately in \( \pm 10 \) A m\(^{-1}\) error for the magnetic field.

In \( G_2 \), the field is high near the excitation winding, and it decreases with the increase of the unwound angle \( \phi \) reaching however its minimum value somewhere in the middle region between the excitation winding edge and the air gap. But due to the presence of an air gap, the field strength is appreciably enhanced toward the air gap. In \( G_2 \), \( \pm 2^\circ \) error in the sensor position along the circumference may result approximately in \( \pm 40 \) A m\(^{-1}\) error for the magnetic field.

Figures 8 and 9 illustrate the sensitivity of sensor positioning, especially for magnetic circuits with air gap, on local field measurements. It is clear that small uncertainty in the sensor position leads to a substantial error in the
measured values, and consequently the inverse problem solution accuracy.

5.3. Quantitative assessment of the measurement accuracy due to stray fields

In order to quantify the measurement accuracy due to the stray field arising at the position of the measurements, it is assumed that the stray field equals the normal component of the total magnetic field at a fixed position, i.e. $H_z$. Figure 10 depicts the percentage error ($\Delta$) in the measured magnetic field value for different stray field values, in $G_2$:

$$\Delta = \frac{\|H_{\text{measured}} - H_{\text{FEM}}\|}{\|H_{\text{FEM}}\|} \times 100\%.$$  \hfill (1)

Again, it is clear that the accuracy of the measurement highly depends on the position of the sensors; the less the stray field the higher the measurement accuracy.

5.4. The effect of stray fields on the magnetic induction measurements

Figure 11 shows the magnetic induction at a specific position in the unwound region of $G_1$, e.g. position 2, using the modified NPM, the NPM with original needles connection (only $V_{12}$) and the quasi-local search coil method. The distance between the two basic needles is 5 mm. It can be observed, from figure 11, that the modified NPM gives a response closer to the reference search coil response. The presented error between the modified NPM and the search coil measurements could be referred to as the error between the ‘quasi-local measurement’ by the search coil and ‘real local measurement’ by the needles, as was discussed in section 3.2.

Moreover, figure 12 compares between the magnetic induction in the unwound area and inside the wound area, in $G_1$. It is clear that the magnetic induction, in the material, inside the excitation coil is greater than that in the unwound area due to the presence of the stray fields. Similar results, with higher field gradient, are obtained for $G_2$.

5.5. Magnetic material characterization fully based on local measurements

Figure 13 shows the $B$–$H$ characteristics of both geometries obtained from local (local $H$ and local $B$ at the same position) magnetic measurements. The characteristics are compared with the original normal magnetizing curve $B$–$H$ curve of the material under test. The magnetizing curve used as the input of the numerical models was obtained by tracing the peak values of both quantities ($B$ and $H$) for different hysteresis loops [23]. A good correspondence between reconstructed magnetic properties using local measurements and original characteristics in $G_1$ is observed, which reveals the accuracy and validates the local magnetic measurements. However, in $G_2$, the accuracy depends on the position where the measurements were carried out. At the position of less stray fields (position 2), a correspondence is observed, while
at the positions of high stray fields (positions 1 and 3), large errors between the recovered characteristic and the original one are observed, especially near the air gap (position 3) due to the double error in the \( B \) and \( H \) local measurements. The results shown in figure 13 confirm the necessity of a numerical inverse approach in order to reconstruct the material properties accurately. Indeed, the reconstruction of the material properties only based on the local \( B \) and \( H \) measurements gives inaccurate results if the local measurements are carried out in a region with high inhomogeneity of \( B \) and \( H \), due to the duplicated errors in both local measurements \( B \) and \( H \). These errors may result from, e.g., not exactly the same position for the \( H \) and \( B \) sensors. The inverse approach can be based only on one local measurement, e.g. \( B_{\text{local}} \), which minimizes the error in the reconstructed properties [11].

From the results presented in the paper, it is clear that the error in the local \( H \)-measurements is higher than the error in local \( B \)-measurements. So, the inverse approach is proposed based on only local \( B \)-measurements rather than local \( H \)-measurements. This coupled experimental–numerical inverse approach is minimizing iteratively the error between the measured and simulated quantity. Moreover, the authors presented an inverse approach based on global measurements (supply voltage and enforced current) in order to recover the material properties of an electromagnetic device [11, 12].

The problem is more difficult in real rotating electromagnetic machines because the material, in such machines, could not be accessible. At that moment, the numerical model can be coupled with local induction measurements at the air gap, or global supply voltage and current or mechanical output measurements in order to reconstruct material properties accurately [24, 25].

6. Conclusion

In this paper, the accuracy of local magnetic measurements is investigated, by performing the measurements on magnetic circuits with highly non-uniform electromagnetic field patterns, like rotating electrical machines.

The presented results show that local magnetic measurements are a challenging task, but are an inevitably task when a coupled experimental–numerical inverse approach has to be solved. In order to solve the inverse problem accurately, the local magnetic measurements have to be accurate, reliable and repeatable. So, in order to obtain accurate magnetic measurements, several aspects have to be taken into account.

- Magnetic measurements should be carried out far from the excitation windings, sample edges and air gap.
- Magnetic sensors should be precisely positioned.

Furthermore, from the results and discussions presented in this paper the following conclusions, concerning the magnetic sensors, are drawn.

- Hall-probe and fluxgate sensors are the best sensors for local magnetic field measurements.
- Magnetic measurement using the flat \( H \)-coil cannot be considered as a ‘real’ local measurement, due to the averaging error.
- The Rogowski coil is highly influenced by stray fields.
- The integration and amplification errors are the main source of errors in a Rogowski coil and a flat \( H \)-coil.
- The local magnetic induction measurements using the needle probe method can be affected by numerous errors, and we proposed a modified connection which gives better accuracy.

Acknowledgments

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