Needle-probe techniques for local magnetic flux measurements

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Numerical two-dimensional field investigations in the cross section of laminated nonoriented electrical steel sheet are performed in order to verify the possibilities and limitations of the two needle-probe technique for the measurement of local magnetic flux near the cutting edge. If one of the needles approaches the lamination edge or when inhomogeneities are present in the flux distribution along the strip width due to magnetic properties altered by the cutting procedure, then the signal from the needle probes no longer represents the flux through a rectangular surface under the needles because of $E$-field components perpendicular to the lamination surface. The flux calculated from the needles is compared to the actual flux passing through the rectangular surface under the needles and corresponding correction factors as a function of the needle position away from the cutting edge are computed. Depending on the positioning method, the needle probes can give an under- or overestimation of the actual flux. Corrections from 15% to 80% are necessary if distances of about the lamination thickness are considered. This work suggests an iterative numerical procedure for the interpretation of experimental data obtained from local flux needle-probe measurements. © 2003 American Institute of Physics. [DOI: 10.1063/1.1544485]

It is known that shaping nonoriented SiFe laminated material into electrical machine laminations by means of punching or laser cutting alters the local magnetic properties near the cutting edge. For the experimental determination of the local magnetic properties, both the local magnetic field and the local magnetic flux density have to be measured.

When a search coil is used to determine the local flux density in laminated magnetic material, one has to make holes in the lamination in order to wind the search coil. This method not only changes the flux pattern but also the mechanical stress state. The needle-probe technique allows nondestructive evaluation of the local flux in the lamination: the time integration of the induced voltage between the needles when considering a high impedance measurement gives rise to the time variation of the local magnetic flux. However, it is more sensitive than the use of search coils.

Among the different error sources, one can distinguish the influence of vertical $E$-field components, the presence of air flux coupled with the wiring connected to the needles, and nonuniformities in the flux distribution caused by the domain structure.

The principle of the needle-probe technique is shown if Fig. 1. Two conditions have to be fulfilled in order to explain why the needles represent the magnetic flux passing through the rectangular area 1234 under the needles with height $d/2$ ($d$ is the lamination thickness). Firstly, the induction $\bar{B} = \bar{B}_x(x,t) \cdot \hat{I}_x$ should have only a space dependency on $x$ and second, both needles are far enough away from the lamination side edge. Both conditions guarantee that the electrical field vector inside the material only has a horizontal component $\bar{E} = E_y(x,t) \cdot \hat{I}_y$, as shown in Fig. 1. Under these conditions, it can be proved that the induced voltage $e(t)$ is given by the change of flux through the gray area shown in Fig. 1, namely $S + S_\tau$. In the following, we will assume that the wiring is carefully done such that the area $S_\tau$ and thus the error introduced by air flux can be neglected.

If one of the needles approaches the lamination side edge or if the material characteristic is not uniform over the cross sectional area, than the electric field vector $\bar{E}$ will have a vertical $E_z$ component. This means that the needles no longer represent the flux through the rectangular surface under the needles. The influence of the edge effect and the influence of a nonuniform material characteristic are separately analyzed in the article.

We consider Maxwell’s second equation, written in integral form

$$\oint_C \bar{E} \cdot d\bar{l} = - \int_S \bar{B} \cdot d\bar{S} = - \frac{\partial \phi}{\partial t}. \quad (1)$$

In fact, the question that should be posed is the following: “Which contour $C$ can we construct that only has a contribution $\bar{E} \cdot d\bar{l}$ between the tips of the needles along the lamination edge?” It will be the surface $S$ enclosed by this contour $C$ that will be considered by the needles. When looking
at Fig. 1, it is indeed the rectangular contour 1234 that only has a contribution along $1 \rightarrow 2$. The other sides of the rectangle 1234 show no contribution since for $4 \rightarrow 1$ and for $2 \rightarrow 3$ $E$ is perpendicular to $dI$ and since for $3 \rightarrow 4$ (this is the center line of the lamination) $E$ equals zero because of symmetry.

We now consider the influence of the edge effect in Fig. 2 and we assume that the material characteristic is uniform over the lamination cross sectional area. Two methods for the needle placement are presented: in Fig. 2(a), both needles are placed on the same side of the sample while in Fig. 2(b) the needles are placed on the same $y$ position but on each side on the lamination. Based on Fig. 2, a qualitative interpretation of the error introduced by the needle-probe technique is given. The induction vector is directed along the $z$ axis and the electric field lines are within the $xy$ plane. In Fig. 2(a), a curve indicating an $E$ line is plotted. When one tries to think of a contour which has no $E \cdot dI$ contribution inside the material, then the tangent line at every point on the contour should be perpendicular to the $E$-field line. This is the case for parts $4 \rightarrow 1$ and $2 \rightarrow 3$ of the contour around area $S$ in Fig. 2(a). Following the first method, where the needles are placed as shown in Fig. 2(a), the needle technique will give the change of flux through the gray surface $S$. This surface is smaller than the rectangular area under the needle tips with height $d/2$. The induction $B_n$ determined from the needle probe will in this case be an underestimated for the actual flux intensity $B_{△}$ passing through the rectangular area under the needles. When the needle-probe technique is used with a needle in the vicinity of the edge of the lamination, the error introduced by the vertical $B_z$ component has to be accounted for. A probable solution is a needle placement following the second method, as shown in Fig. 2(b). The needles in this case envisage the area $S$ in Fig. 2(b). In this case, the needles will give an overestimation of the actual flux intensity $B_{△}$ through the rectangular surface between the needles.

By means of two-dimensional finite element computations, the influence of the edge effect on the results given by the needle probe and under uniform flux is qualitatively examined. A lamination with thickness $d=0.5$ mm and with a single-valued nonlinear material characteristic (Fig. 3, with $s=0$) is considered. A sinusoidal induction is applied. The cross section of the lamination is divided into finite elements, and for each second order element the $H$ values are determined in the corners and in the middle of each side. These local $H$ values are subsequently used in two ways.

On the one hand, starting from $H(x,y,t)$ and by using the expression $J=\nabla \times H$, the $J$ lines are determined. From this, the $E$ lines on the edge of the lamination are calculated. We consider both methods for needle placement as shown in Fig. 2. In the first method, the left needle is kept fixed at the edge of the lamination ($y=0$) and the right needle is moved from $y_n=0.1d$ to a position $y_n=4d$. For each position $y_n$ of the right needle, the time integral of $\int_0^{y_n} E_x(y,t)dy$ is calculated and the induction $B_{n,met1}$ given by the needles is determined. In the second method of needle placement, $B_{n,met2}$ is obtained in a similar way.

On the other hand, the local $H(x,y,t)$ values are used to calculate the local $B(x,y,t)$ values. By spatial integration of $B(x,y,t)$ over the domain $0<x<d/2$, $0<y<y_n$ (method 1) or $-d/2<x<d/2$, $0<y<y_n$ (method 2), the induction $B_{△}$, representing the induction in the rectangular area under the needle tips with height $d/2$, can be determined.

From the comparison of the actual induction $B_{△}$ through the rectangular surface with the induction $B_n$ obtained by the needles, correction factors $B_{△}/B_n$ are calculated as a function of the needle position. The results are shown in Fig. 4. An average induction of 1 T at 50 Hz is considered. In the first method, the correction factors exceed 1 and thus the needle technique indeed gives an underestimation of the induction for low $y_n/d$. In the second method, correction factors less than 1 are obtained which indicates that the needle technique here gives an overestimation of the actual flux. In comparison with the first method, the second way of needle placement results a lower necessary correction.

When investigating the local magnetic properties of the lamination near the cutting edge, in addition to the geometrical edge effect, the magnetic characteristic will also differ from the characteristic of the bulk material. A change in the

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local material characteristic will also introduce $E$ components in the $x$ direction and will influence the needle technique. In order to examine this influence apart from the geometrical edge effect, a lamination with varying material characteristic is considered in Fig. 5. The variation of the plastic deformation parameter $s$ varies from 10 (for $y/d=0$) to 0 (for $|y/d|>3$).

The following values are used in the computations: $a_0 = -201.7$ (J/m$^3$), $b_0 = 801.5$ (H/m$^{-1}$), $a_1 = 0.028$ (T$^{-1}$), $b_1 = 0.508$ (T$^{-1}$), $a_2 = 1.656$ (J/m$^3$)$^{-1}$, $b_2 = -4.96$ (J/m$^3$)$^{-1}$, and $\Delta H(s)$ varies monotonically, increasing from $\Delta H(0) = 43$ to $\Delta H(10) = 437$. The variation $s(y/d)$, as shown in Fig. 5, is given by the expression:

$$s(y/d) = \frac{1}{|y/d|} + a_3 + b_3,$$

FIG. 5. Schematic for the study of the influence of a nonuniform material characteristic; the greyed cross sectional area corresponds to the affected surface and has lowest permeability in the center ($y/d=0$); the plastic deformation parameter $s$ varies from 10 (for $y/d=0$) to 0 (for $|y/d|>3$).

FIG. 6. Evolution of the electric field $E_y(y,t)$ along the lamination edge when applying a 50 Hz sinusoidal induction with an average of 1.4 T.

FIG. 7. Correction factors for inhomogeneous flux distribution in: (a) for an average peak induction of 1 T and in (b) 1.4 T.
in which $a_3 = 0.01152$ and $b_3 = -76.8$. The left needle in Fig. 5 is kept in the same position $y=0$, while the right needle can be moved.

The same methodology as described above was used to determine $B_n$ and $B_\parallel$. In Fig. 6, the evolution of the $E$-field variation along the lamination edge is shown for an applied average induction of 1.4 T at 50 Hz. The 16 different curves correspond to 16 different equidistant points in a time during a 20 ms period. The full lines show the electrical field at points in time during the rising part of the period while the dashed lines correspond to the falling part of the period. The influence of the region with altered magnetic properties can be clearly seen. The correction factor obtained by comparing $B_n$ and $B_\parallel$ is shown in Fig. 7. Two different induction levels and three magnetization frequencies (50, 100, and 200 Hz) are considered. Figure 7(a) shows the results for an average peak induction of 1 T and Fig. 7(b) for 1.4 T. The horizontal axis in the graphs in Fig. 7 corresponds to the position $y_n$ of the right movable needle while the left needle is kept in the middle of the lamination (position $y/d=0$). The results indicate that the needle technique in this case gives an overestimation of the actual flux through the rectangular area under the needles. This can be explained qualitatively. Since the material characteristic deteriorates when approaching the center area of the lamination, the flux level in the center area will be lower for the same $H$ value along the lamination surface, and $E$-field lines will deflect from the lamination edge similar to what has been shown in Fig. 2(a). If one constructs a contour which has no $\bar{E} \cdot d\bar{l}$ contribution inside the material, then this contour should look similar to what is shown in Fig. 2(b). The area that is considered by the needles thus is larger than the rectangular area under the needles, which leads to a correction less than one. To conclude, in practice both effects are present simultaneously and the reconstruction of the actual flux distribution through the lamination must be done by using an iterative numerical procedure for the interpretation of the experimental data from local flux needle-probe measurements.

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