EMC of an induction motor: Measurements compared to calculations

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Abstract— **When studying EMC, which is an important aspect in machine designs, the field in the area outside of the machine is of interest and it should not influence any magnetic devices. This lecture presents measured results compared with calculated results obtained with Maxwell 2D. It is concluded that under certain assumptions 2D FEA is sufficient when designing or analyzing machines to meet the EMC requirements.**

I. INTRODUCTION

The field outside of an induction motor might negatively influence magnetic devices. It is therefore important to take EMC requirements into account when designing induction motors. Throughout this paper it is assumed that the analysis holds for a stand-alone induction motor without any magnetic material in the surrounding space. Calculated flux densities are on a surface that represents a cross-section at the middle of the motor. It is the aim to investigate a general method on how EMC can be accounted for by means of 2D FEA, and where possible, to compare the calculated result with measurement. The main objectives are:

1) Determine the influence on the field outside of the stator when varying the magnetizing current.
2) Determine the effect of housing on the magnitude of the field outside the motor.
3) Comparison of the calculated results with those measured.

A. Problem statement

Magnetic sensors and pacemakers can be influenced by the magnetic flux density. Depending on the EMC requirement a specific flux density vector-component or the time signal of the flux density is of importance. This paper investigates two vector-components of the flux density as well as the harmonics for a supply frequency of 20 Hz.

B. Approach to the problem

As a first approximation it is sufficient to use a 2D FEA model of the motor. This means that a two dimensional surface needs to be defined where the field is to be evaluated. The surface represents a cross section of the motor and must be large enough to include the surrounding space. The flux density will then be calculated and evaluated at the positions where measurements were done. A harmonic analysis of the flux density as function of time will give information about the harmonic content and how it is affected by the operating conditions. Since the flux density is a vector quantity, the vector-components needs to be analyzed as well. When however, the flux density of interest does not lie in this surface a 3D model should be used. Furthermore, if the surrounding space of the motor contains other materials that influence the field distribution a 3D model should be considered.

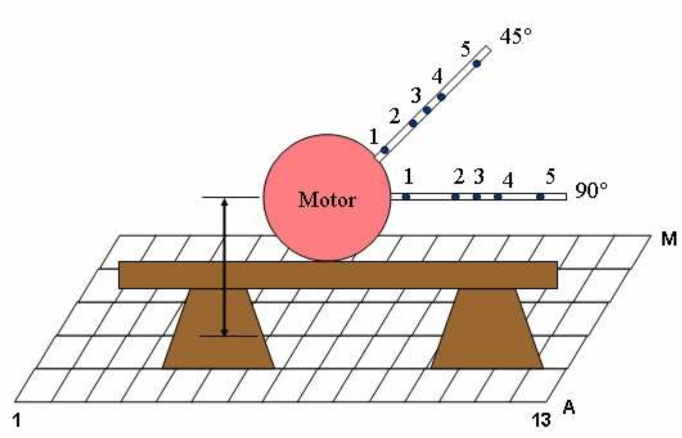

Fig. 1. Measurement setup showing the grid and lines along which the measurements are taken.

II. MEASUREMENTS

The flux density was measured on a grid at a certain level below the motor and along a line at a given angle. A typical measurement set-up as in Fig. 1 shows the grid below the motor and lines at which the measurements were taken. The motor used has no housing, as the stack is supported by four support brackets. Measurements used in the comparison were made on a stand-alone motor, thus no magnet material in the surrounding. Firstly, this makes a fair comparison with the calculation, since a 2D FEA model is used. Secondly, the accuracy of modeling the field is to be evaluated. The flux density was measured at the following three positions as in Fig. 1:

1) on a grid that is a defined distance from the center of the shaft below the motor,
2) pre-defined points along a line at 45 and
3) pre-defined points along a line at 90.

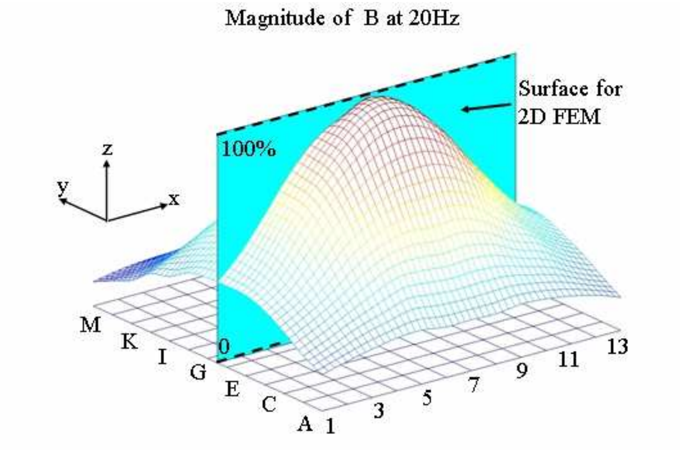

Fig. 2. Flux density magnitude of the 1st harmonic at 20 Hz supply frequency.

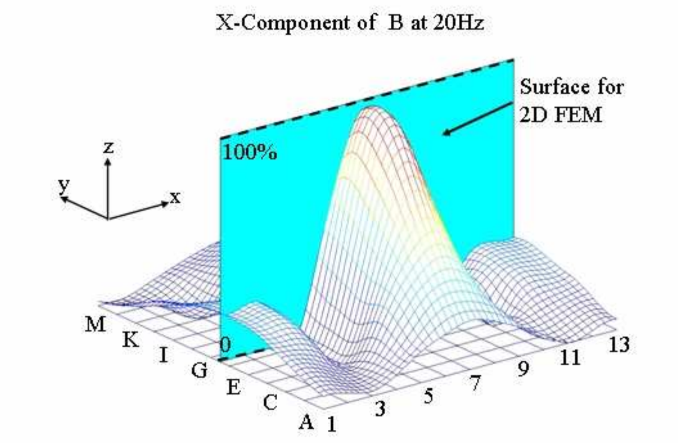

Fig. 3. 1st Harmonic of the x-vector component of the flux density at 20 Hz supply frequency.

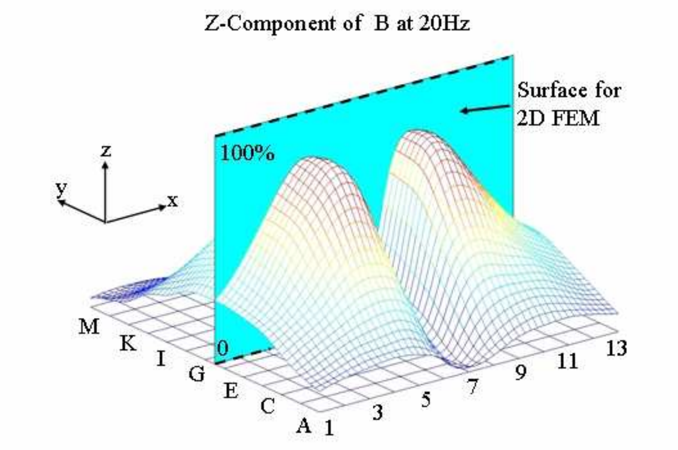

Fig. 4. 1st Harmonic of the z-vector component of the flux density at 20 Hz supply frequency.

For the measurements the motor was set well above the ground on wooden blocks. This prevents the magnetic field from being influenced. The grid had rows A to M, and columns 1 to 13 as shown in Fig. 1. Columns 1 to 13 represent the x-axis. Columns A to M represent the y-axis. A vertical surface for modeling is between columns F and G. The surface is perpendicular to the xy-plane and represents the z-axis. Using this coordinate system the x- and z-components are to be measured and calculated. At each of the grid points the following measurements on the flux density at 20 Hz were performed:

1) the vector magnitude of the 1st harmonic and
2) the magnitude of the 1st, 3rd and 5th harmonics for the x- and z-vector components.

A. Measured results

Due to saturation of the laminations the harmonic components have to be measured using a bandpass filter. The vector magnitude of the 1st harmonic is shown in Fig. 2. For the visualization a 2D interpolation function was used on the measured data to generate a 3D surface of the flux density. The absolute maximum value is used as reference and equals 100%. The x- and z-vector components are shown in Figs. 3 and 4 respectively. Since a 2D FEA model is used, the cross-cut at the middle of the motor corresponds to the surface as shown in the Figs. 2-4. The graph as a result from the intersection of the 2D surface and the measurement is used for the comparison between measurement and calculation.

In Fig. 3 the maximum of the x-vector component in the middle of the motor (F7 on the grid) almost equals the absolute maximum. The z-vector component in Fig. 4 tends to zero at the middle and increases when moving away from the middle in a x-direction. It has two maximum values and is approximately 80% from the absolute maximum.

III. FINITE ELEMENT MODELING

General techniques of analysis of induction machines are well known [1]-[5]. Calculation of the time-signal implies that a time-domain analysis must be chosen. The dynamic modeling approach has been implemented and takes into account the rotation of the rotor. The motion equation is coupled with the field and circuit equations to consider mechanical transient through electromagnetic torque. In order to obtain a time signal of the flux density, the Maxwell 2D transient solver is chosen.

A. Maxwell 2D model

A rule of thumb when the background is included into the FEA model is that the object modeled must be at least a fifth of the total model size. In this case the total model size must be at least 5 times the stator outer radius. The outer boundary of the model is then assumed to be at infinity. In the boundary set-up the balloon boundary condition is assigned to the background. The assumption that the vector potential on the stator outer boundary equals zero does not hold, when the field outside the motor is of interest. In order to get a proper solution in the region of interest, some dummy objects are created. It has the same material property as air in this case and are

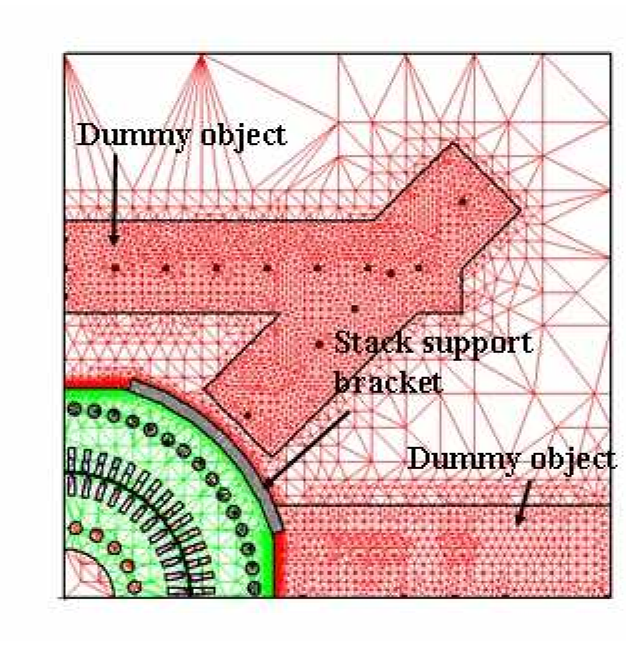

Fig. 5. FEA mesh showing the dummy elements.

used to control the density of the mesh. Thereby avoiding a too large number of elements. The FEA model is shown in Fig. 5. The support brackets are solid material which implies that eddy currents will be induced. Calculating eddy currents using Maxwell 2D a current source having zero value must be assigned to the stack support bracket. In this way the integral of the current density over the bracket surface will be zero. Letting S be the surface of the support bracket the following holds:

$$\int_S \mathbf{J} da = 0 \tag{1}$$

In the simulation the support bracket will be either assigned the property of air or that of solid steel. This way the effect of the stack support brackets can be calculated. The laminations were modeled having no conduction properties in the axial length.

B. Excitation option

In case of the transient solver Maxwell 2D offers either current or voltage excitation. The use of an external circuit is also possible. For this study the voltage excitation was used. The three-phase instantaneous voltages are defined as follows:

$$u_a = U_{LL}\sqrt{2/3}\, cos\,(\omega t) \tag{2}$$

$$u_b = U_{LL}\sqrt{2/3}\, cos\left(\omega t - \frac{2\pi}{3}\right) \tag{3}$$

$$u_c = U_{LL}\sqrt{2/3}\, cos\left(\omega t - \frac{4\pi}{3}\right) \tag{4}$$

As a first check the measured no-load current is compared with that calculated. This way the model can be verified.

C. Harmonic analysis

The field solution gives the magnitude of the flux density as result. This vector has only the x- and z- components in a 2D model. The x- and z-components as a function of time are calculated in the following way: The vector component is integrated over a small surface at each of the measuring points, which is then averaged by the surface area. This results in the average flux density at the given point. The surfaces where the average flux densities are calculated are shown as the black circles in Fig. 5. A macro is used to perform this operation after each time-step. The components are calculated after each time-step as follows:

$$B_{x,average} = \frac{1}{A}\int_S B_x da \tag{5}$$

and

$$B_{z,average} = \frac{1}{A}\int_S B_z da \tag{6}$$

where S the surface of integration and A the area are. At each of the sampling points a time function, $B(t)$, is obtained. Having the vector-components as time functions a Fourier analysis is performed. The resulted function has the following form

$$B_x(t) = \sum_{n=1}^{1,3,5} B_{x,n} cos(n\omega_0 t) \tag{7}$$

and

$$B_z(t) = \sum_{n=1}^{1,3,5} B_{z,n} cos(n\omega_0 t) \tag{8}$$

where B_n represent the n^{th} harmonic of the calculated flux density.

Since a transient solver is used, the time-step should be sufficient small to include all the harmonics and to avoid aliasing. If ν is the highest harmonic and f_1 the fundamental frequency the sampling time can be calculated using

$$T_s = \frac{1}{2f_1\,(\nu + n)} \qquad \text{for } n = 1, 2, 3, \cdots \tag{9}$$

The variable n is only used to assure that the sampling frequency is higher than twice the highest frequency component and by choosing it as an integer implies that the resolution in the frequency domain when using a DFT will be a multiple of the fundamental frequency.

IV. COMPARISON BETWEEN MEASUREMENT AND CALCULATION

The 2D FEA model is first verified by calculating the 1^{st}, 3^{rd} and 5^{th} harmonics of the flux density for different magnetizing currents. In each of the calculations the supply frequency is 20 Hz. Fig. 6 shows the results which were calculated at a defined distance below the motor. This corresponds to a point in the grid at F7. From the figure it is clear that for each of the harmonics the flux density increases with an increase in the magnetizing current. The harmonics obtained from the FEA model are calculated by performing a Fourier analysis on the calculated flux density as a function of time as described in section III-C.

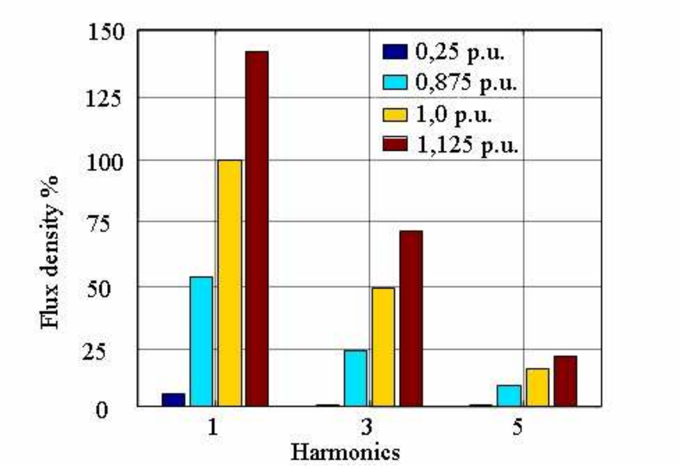

Fig. 6. Flux density harmonics for different magnetising currents measured at F7 on the grid.

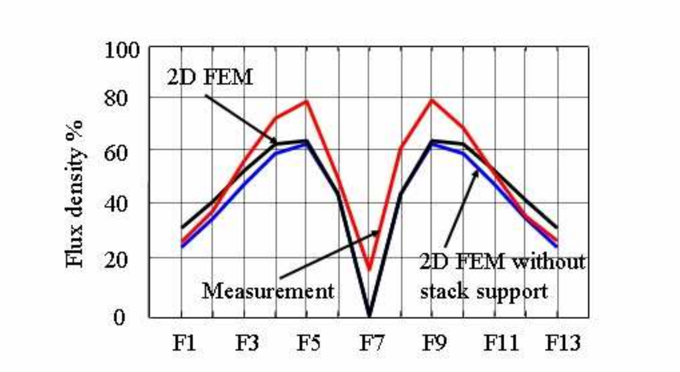

Fig. 7. 1st Harmonic of the x-component along F.

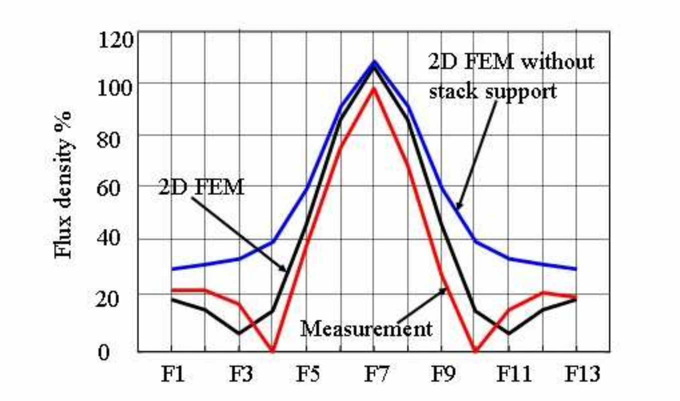

Fig. 8. 1st Harmonic of the z-component along F.

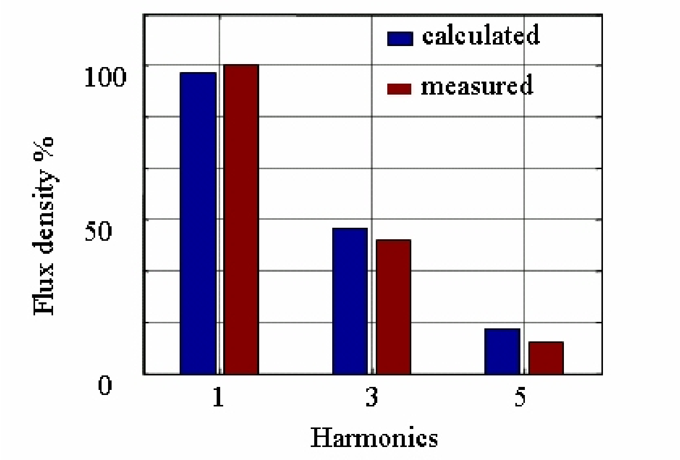

Fig. 9. Harmonics at F7 of the flux density at 20 Hz supply frequency and 1 p.u. current.

A. x-Components

The measured x- and z-components along the row F, at 1 p.u. current, of the flux density together with the calculated results are shown in Fig. 7 and Fig. 8 respectively. Note firstly that the x-component of the flux density has its maximum at the center of the motor (F7) and decreases when moving away from the center. The calculated results also show the effect of the stack support brackets. Without the stack support brackets the maximum flux density is much higher. Especially at F4 and F10 the values are less then half with stack support than without support brackets. The calculated flux density with stack support brackets along the total distance shows good correlation with the measured values. This clearly shows that the stack support brackets decrease x-components of magnetic field in the region of the brackets.

B. z-Components

Fig. 8 shows that the z-component tends to zero at the middle of the motor. Moving outwards from the center, the z-component first increases up to F5 and F9 and then decreases again. The effect of the support brackets is clearly smaller than in the x-components. Measured results in Figs. 7 and 8 are the intersection with the 2D surface in Figs. 3 and 4 respectively.

C. Harmonics

The following calculated results presented are compared with measurements at rated magnetizing current, (1 p.u.), and at 1,125 p.u. Measured and calculated spectrums of the flux density at different magnetising currents are shown in Fig. 9 and Fig. 10 respectively. For each measured harmonic a bandpass filter was used. Comparison of the calculated results with the measurements at 1 p.u. current, shows a good correlation. However, at 1,125 p.u. current, the calculated flux density is higher than that measured. An increase in the magnetising current shows an increase in the flux density as well. Only harmonics up the the 5th were measured.

V. CONCLUSION

A general method has been presented to account for EMC requirements in the design of induction motors. It makes use of a 2D FEA model and suggests step-by-step procedure to analyse and evaluate the results. The comparison of calculation was satisfactory when compared to the measurement. From

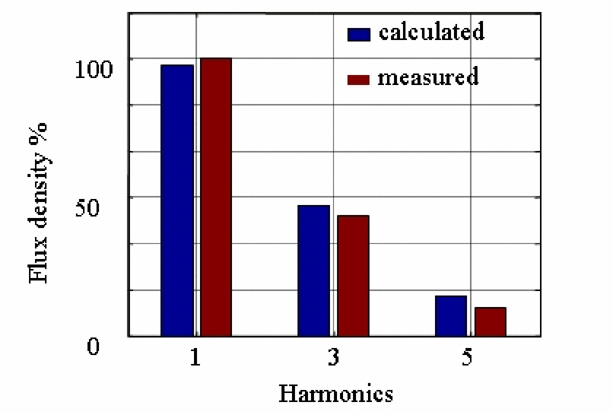

Fig. 10. Harmonics at F7 of the flux density at 20 Hz supply frequency and 1,125 p.u. current.

the similar trends of the measured and calculated data at the middle of the motor, one can conclude that the FEA can be used to investigate and improve the machine design to be electromagnetically compatible. The typical field distribution of a motor having no other magnetic materials in its surrounding, are shown in Figs. 2-4. If the flux density is calculated with a 2D FEA tool at the middle of the motor, it can be approximated elsewhere.

The effect of the stack support was investigated and the results of this indicate that the stack support reduced the field density outside of the motor. The influence of housing on the field outside of the motor was not investigated. However, one can conclude that housing will further reduce the field density outside of the motor.

The 2D model is only valid in the plane where the calculation was done. For calculating flux densities in any other plane, a 3D model is to be used. The 2D model has the disadvantage that it does not take into account the fact that the motor is not homogeneous axially e.g. the stack support brackets are not straight from one end of the motor to the other.

When the time signal is of importance the flux should be measured without a filter. In this case the phase difference between the harmonics will determine the absolute maximum value.

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