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FEM-3D FOR METROLOGICALLY IMPROVED MAGNETIC MEASUREMENTS

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The Epstein frame as an electrical steel sheet testing apparatus forms an unloaded transformer with a magnetic core of the electrical steel sheet test specimen. It is an electromagnetic system, with non-linearity introduced by the magnetic material under test. For exact metrological estimation of the magnetic characteristics of the electrical steel sheet, the magnetic field distribution has to be well known. The finite element method in three-dimensional domain, embedded in the original program package FEM-3D is used for exact calculation of the effective magnetic path length for three grades of reference test specimen under different magnetic polarizations. The leakage fluxes in the air are also numerically calculated. The FEM-3D results are used for exact design of the air flux compensation coil of the Epstein frame. The numerically derived results are experimentally verified through testing of the developed prototype of new metrologically improved Epstein frame in a laboratory.

Keywords: finite element method, Epstein frame, magnetic measurements

1 INTRODUCTION

Very frequently applied magnetic measurements are the experimental methods for estimation of the magnetic properties of the electrical steel sheets. These procedures are standardized in two main standards IEC 60404-2, [1] and IEC 60404-3, [2]. The Epstein Frame (EF) in [1] forms an unloaded transformer with a magnetic core of the electrical steel sheet test specimen. The results of magnetic properties measurements can be affected by many different influences, which can be divided into four categories:

1. Properties of the material (type, thickness, density, orientation, treatment);
2. Magnetic circuit (the type of the device: Epstein frame or Single Sheet Tester, length of the sample, magnetic path length, cross sectional area, number of turns, mass);
3. Parameters (peak value of polarization, curve shape of polarization, frequency, temperature);
4. Electrical measurements (voltage, current, power).

The contribution of the certain influencing quantities to the uncertainties budget during the process of magnetic properties measurements of electrical steel sheet has been analysed in [3].

Epstein frame is an electromagnetic system, with non-linearity introduced by the magnetic material under test. For exact metrological estimation of the magnetic characteristics of the electrical steel sheet, the magnetic field distribution has to be well known. The standard [1] introduces several approximations:

a) constant magnetic path length l_m=0,94 m;
b) approximate magnetic field distribution;
c) not exactly calculated leakage fluxes in the air.

The presumption of constant, invariant to the specimen grade effective magnetic path length l_m = 0.94 m, leads to an undefined systematic error. The magnetic path length l_m is used for calculation of the magnetic field strength (peak and RMS), the specific power losses P_s, and the specific apparent power S_s.

In recent years there are numerous publications on scientific contributions for finite element modelling of non-linear electromagnetic systems with special emphasis on magnetic materials, [4], and [5]. In this paper a new approach for numerical estimation of the magnetic field distribution in the Epstein Frame, by using an originally developed computer program based on 3D finite element method FEM-3D, will be given, [4]. The FEM-3D results enable an EF prototype design with reduced measurement uncertainty, which will be experimentally verified at the Metrological laboratory for electromagnetic quantities at the Ss. Cyril & Methodius University, Faculty of Electrical Engineering and Information Technologies-Skopje.

2 FEM-3D ANALYSIS OF EPSTEIN FRAME

The finite element method is one of the most convenient tools for analysis of complex and bounded electromagnetic systems with prescribed boundary conditions. For the analysis of the measurement devices in this paper an original programme package FEM-3D, based on the Weighted Residuals Method, developed at the Ss. Cyril & Methodius University, the Faculty of Electrical Engineering and Information Technologies will be used, [4].

The magnetic field distribution in closed and bounded systems, like the EF, is described by the system of Maxwell's equations. After the magnetic-vector potential $\vec{A}$ as an auxiliary quantity is introduced, the magnetic field distribution is expressed by the system of Poison's nonlinear partial differential equations of the following kind

$$\frac{\partial}{\partial x}\left(\vec{\nu}\left(\vec{B}\right)\frac{\partial \vec{A}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\vec{\nu}\left(\vec{B}\right)\frac{\partial \vec{A}}{\partial y}\right)+\frac{\partial}{\partial z}\left(\vec{\nu}\left(\vec{B}\right)\frac{\partial \vec{A}}{\partial z}\right)=-\vec{j}(x,y,z) \quad (1)$$

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where $\vec{B}$ is the magnetic flux density, $\vec{\nu}$ is the magnetic reluctivity and $\vec{j}$ is the volume current density.

The programme package FEM-3D comprises five main modules:

G1 - automatic mesh generator;
G2 - flux plot;
G3 - input definition of boundary conditions, material properties and magnetizing current sources;
G4 - magnetic field distribution calculator;
G5 - electromagnetic characteristics calculator.

The three-dimensional FEM analysis is done by taking into account the magnetic anisotropy and the different magnetic reluctivities along the co-ordinate axes, due to the lamination of the magnetic cores of the devices. The detailed description of the FEM-3D program package has been previously given in [4].

The EF FEM-3D analysis is done for three different grades of electrical steel sheet. In Table 1 the results from the FEM-3D post processing are given (the dependence of the effective magnetic path length on the magnetic polarization and the grade of the specimen).

Table 1. Numerically calculated effective magnetic path length l_m for three grades of electrical steel sheet

J_m (T)		l_m (m)	
	Grade A	Grade B	Grade C
0.200	0.985	0.989	1.008
0.400	0.983	0.989	0.989
0.600	0.983	0.989	1.000
0.800	0.979	0.990	0.995
1.000	0.957	0.990	0.981
1.200	0.930	0.990	0.939
1.400	0.924	0.990	0.871
1.600	0.909	0.961	0.900
1.800	0.937	0.893	0.888

From the results in Table 1 it can been concluded that the effective magnetic path length is higher than 0.94 m (as in [1]) at lower values of the magnetic polarization J_m. and lower than 0.94 m at higher values of the magnetic polarization. The value of 0.94 m effective magnetic path length, which is adopted in the IEC standard [1], can be applied for the values of magnetic polarizations from 1 to 1.3 T (the knee of the magnetic characteristics).

3 EXPERIMENTAL VERIFICATION OF THE FEM-3D NUMERICAL RESULTS

The FEM-3D numerical results are used for the design of the new metrologically improved prototype of the Epstein frame. developed and realized in the Transformer production company EMO A.D.-Ohrid. R. Macedonia. The numerically derived results for the leakage fluxes in the air are used for exact calculation and design of the air flux compensation coil of the prototype. The FEM-3D metrologically improved design of the air flux compensation coil is given in Fig. 1 and Fig. 2.

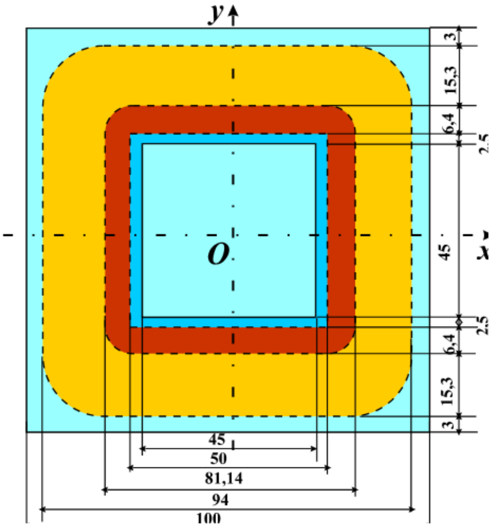


Fig. 1. Cross-sectional aspect of the air-flux compensation coil

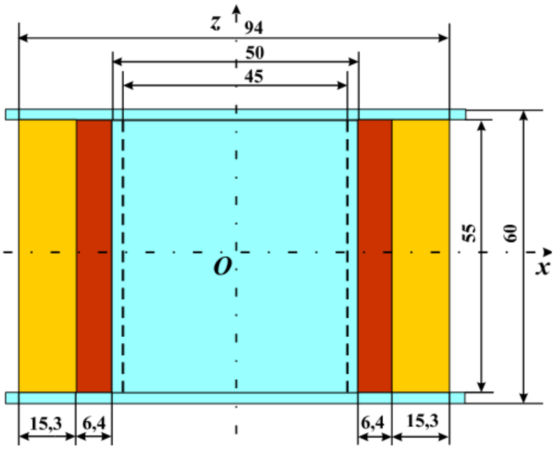


Fig. 2. Axial aspect of the air-flux compensation coil

The realized prototype of the Epstein frame is displayed in Figure 3.

The prototype is tested in the Metrological Laboratory for Electromagnetic Quantities at the Faculty of Electrical Engineering and Information Technologies – Skopje.

Fig. 3. Realized prototype of the Epstein frame

The experiments are carried out according to the IEC standard specifications [1]: for magnetic polarization from 0.1 to 1.8 T. with step of 0.1 T at frequency of 50 Hz, at sinusoidal waveform and form-factor ξ = 1.111. The testing circuit is given in Fig. 4.

The comparison of the analytically (by using the classical analytical transformer theory), numerically (by using the FEM-3D calculation of the effective magnetic path length and taking into account the magnetic anisotropy and lamination of the electrical steel sheet, as well as main flux and leakage fluxes distribution) and experimentally (through testing of the developed prototype for metrological laboratory) derived magnetic properties of one of the electrical steel sheet is displayed in Fig. 5 and Fig. 6.

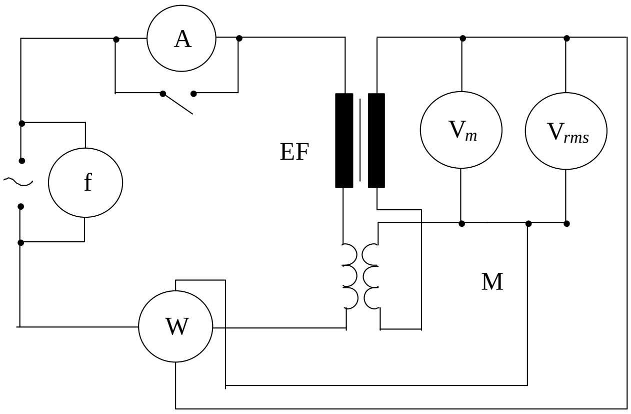
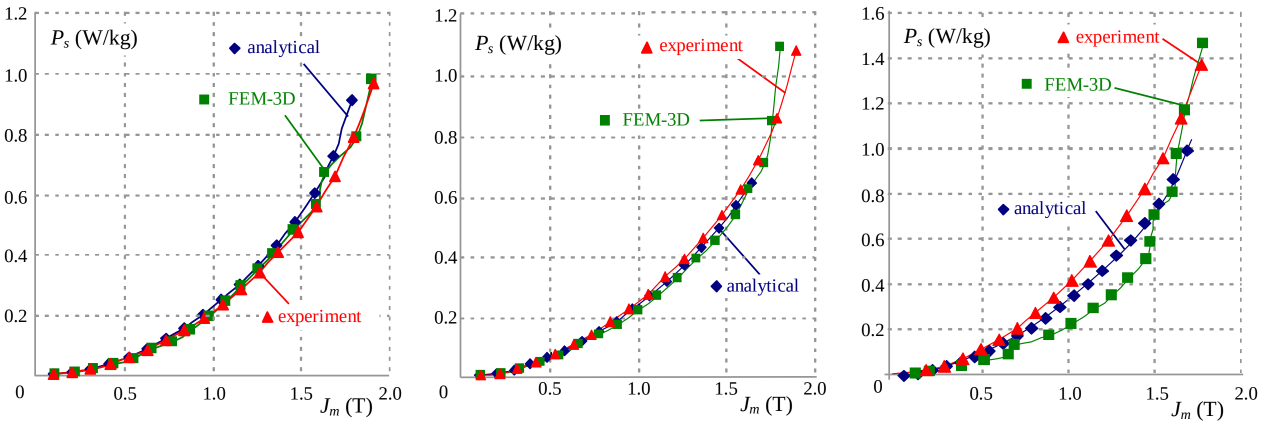
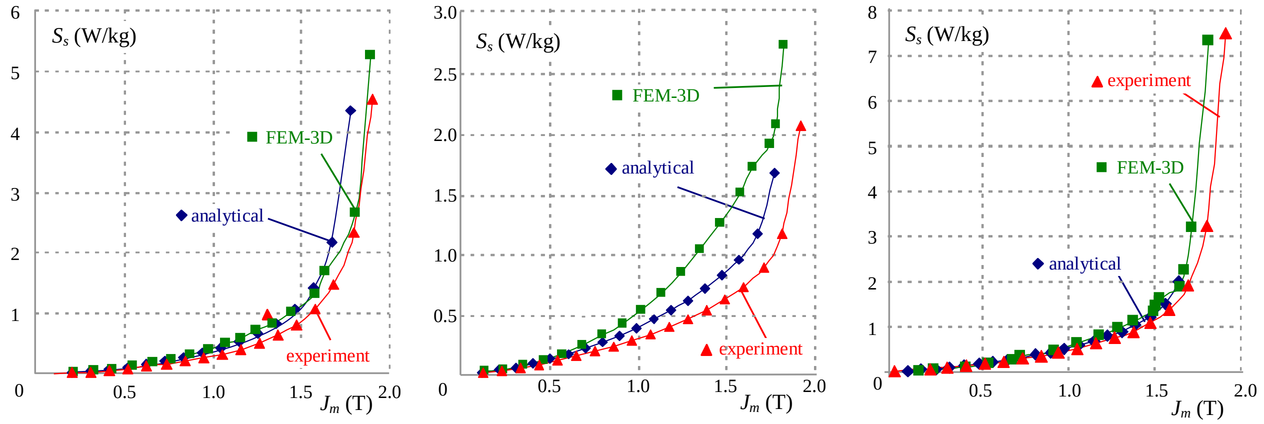


Fig. 4. Test circuit for experimental verification



(a) Grade A (b) Grade B (c) Grade C

Fig. 5. Comparison of the specific power losses characteristics derived by the analytical, numerical and experimental method for three grades of the referent electrical steel sheet test specimen



(a) Grade A (b) Grade B (c) Grade C

Fig. 6. Comparison of the specific apparent power characteristics derived by the analytical, numerical and experimental method for three grades of the referent electrical steel sheet test specimen

4 CONCLUSIONS

In the paper a FEM-3D approach to the magnetic measurements procedures is made. A metrologically improved construction of a prototype is enabled with reduced systematic errors. In the paper an original approach to the magnetic measurements procedures for testing of electrical steel sheet characteristics coupled with three-dimensional electromagnetic field analysis is made. A considerable reduction of the systematic errors is made through the exact numerical calculation of the effective magnetic path length as well as through the accurate design of the air flux compensation coil which has been experimentally verified for different physical characteristics of the electrical steel sheet test specimen on the prototype in a laboratory. The experiments show good agreement to the numerical results. Especially in the specific power losses characteristics. In the case of the apparent power and power factor characteristics besides the effective magnetic path length contribution in the measurement uncertainty budget there are also other contributions, which could be analysed in further research.

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