APPLICATION OF NUMERICAL METHODS IN CALCULATION OF ELECTROMAGNETIC FIELDS IN ELECTRICAL MACHINES

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Abstract: *Finite Element Method has been proved as valuable tool for solving different electromagnetic problems inside electrical machines. Calculation of magnetic flux density and its distribution in machine cross-section is difficult to be calculated by analytical methods. Therefore Finite Element Method is implemented for solving set off Maxwell equation which enables precise calculation of electromagnetic field and magnetic flux density in three different electrical machines: three phase squirrel cage motor type 5AZ801-4 prodct of company Rade Koncar, three phase distribution transformer type product of company EMO, and single phase capacitor motor FMR-35/6 product of company MikronTech. Distribution of magnetic flux density in all three machines is calculated for different operating regimes.*

Keywords: Finite Element Method, three phase squirrel cage motor, three phase distribution transformer, single phase capacitor motor

1. Introduction

Calculation of electromagnetic fields inside machine cross-section is always a challenging task and often it implements numerical calculations based on Finite Element Method (FEM) which enables solving the set of Maxwell equations and obtaining the value of magnetic vector potential and magnetic flux density in all parts of machine cross section. On that way possible “week” parts of machine construction can be discovered i.e. parts where flux density reaches high values and machine operates near to saturation point of magnetic core. In this paper three different machines are analyzed: three phase squirrel cage motor *5AZ801-4* product of company Rade Koncar from Zagreb single phase capacitor motor FMR-35/6 product of company EMO MikronTech from Prilep (Fig.1), three phase transformer product of company EMO from Ohrid (Fig.3).

(a) (b)

Fig. 1. *Physical layout of (a) squirrel cage motor (b) single phase motor*

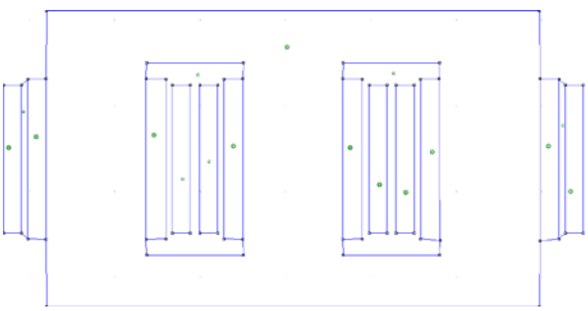
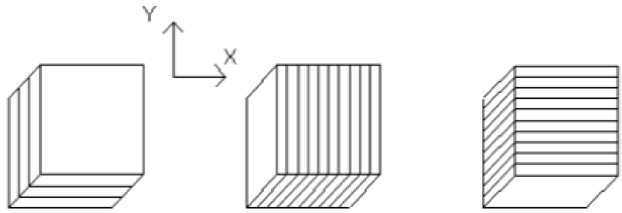


Fig. 2. *CAD drawing of three phase transformer*

Rated data of three phase motor 5AZ80-1/4 are: stator winding connection: D/Y, rated voltage 230/400, rated current 2,8/1.6 , rated power 0.55 kW, power factor cosφ=0.76, rated speed 1390 rpm. Rated data of single phase capacitor motor FMR-35/6 are: rated voltage 220-240 V, rated power 180 W, rated current 1,32 A, rated speed 2880 rpm. Rated data of transformer are: rated power 50 kVA, voltage 10/0.4 kV, Yzn5, short circuit voltage 4 %.

2. Methodology of FEM

Finite Element Method (FEM) is a numerical method used for solving relatively complex electromagnetic problems where material nonlinearity and anisotropy is included in analyzed domain. Method involves discretization of the whole analyzed domain in small triangle surfaces, which are called finite elements. By applying Maxwell’s equations into FEM it is possible to calculate the stationary distribution of magnetic field inside electrical devices. The FEM analysis of the analyzed object is divided into three parts: pre-processing, processing and post-processing part. In pre-processing part the object geometry, as well as boundary conditions are defined. For all machines are chosen Dirichlet boundary conditions e.g. A=0. The most common use of Dirichlet-type boundary conditions in magnetic problems is to define A=0 along a boundary to keep the magnetic flux from crossing the boundary. Properties of all materials are input in object model. Beside inputting the magnetization curve as B=f(H) also the lamination of magnet material is input according to Figure 3 (a) as well as fill factor. The result of this model is that one can account for laminations with hysteresis and eddy currents. In order the value of the magnetic vector potential A to be determined it is necessary the whole domain i.e. object cross-section to be divided into a certain number of elements.



(a) (b) (c)

Fig. 3 *Laminations of magnetic steel sheets in FEM models*

The number of elements is problem dependent and for transformer model the finite element mesh is consisted of N=17833 nodes and E=35089 elements (Fig.4) while for the three phase motor model N=34 751 nodes and E=74724 elements (Fig.5). For single phase capacitor motor finite element mesh is consisted of N=51 638 and E=102850 elements. (Fig.6).

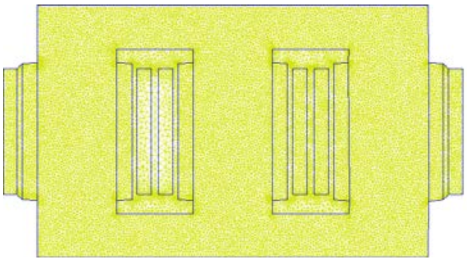


Fig. 4 *FEM mesh in transformer*

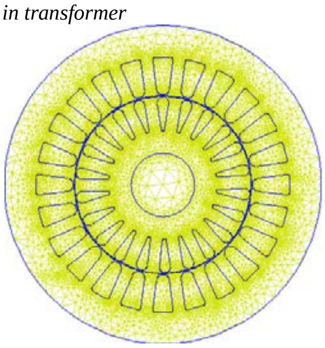


Fig. 5 *FEM mesh in three phase motor*

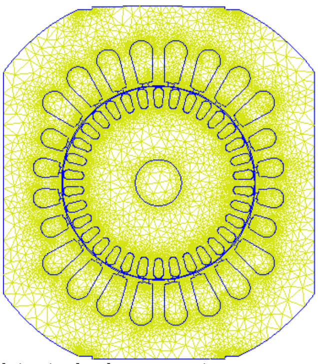


Fig. 6 *FEM mesh in single phase capacitor motor*

In order processing part to be executed and output results to be obtained system of Maxwell's equation should be solved. They differ in both cases: magnetostatic and time-harmonic.

Magnetostatic problems are problems in which the fields are time-invariant [1]. In this case field density **H** and flux density **B** must obey:

$$\nabla x\mathbf{H} = \mathbf{J} \tag{1}$$

$$\nabla x\mathbf{B} = 0 \tag{2}$$

subject to a constitute relation between B and H for each material:

$$B = \mu H \tag{3}$$

FEM goes about finding a field that satisfies (1)-(3) via a magnetic vector potential. Flux density is written in terms of vector potential **A** as:

$$B = \nabla x A \tag{4}$$

For the magneto-static problem the non-linear B-H relation FEM solves the equitation:

$$\nabla x\left(\frac{1}{\mu(B)}\nabla xA\right) = J \tag{5}$$

The advantage of using the vector-potential formulation is that all the conditions to be satisfied have been combined into a single equation. If magnetic vector potential A is found, B and H can be deduced by differentiating A. After exact machine geometry is input boundary conditions are defined. For this specific motor model are chosen Dirichlet boundary conditions e.g. A=0. The most common use of Dirichlet-type boundary conditions in magnetic problems is to define A=0 along a boundary to keep the magnetic flux from crossing the boundary. When analysing induction machines, considering their AC excitation the air gap magnetic field is always a time-varying quantity [2]. In materials with non-zero conductivity eddy currents are induced, consequently the field problem turns into magnetodynamic i.e. non-linear time harmonic problem. When rotor is moving, the rotor quantities oscillate at slip frequency .In this case the rotor bars conductivity σ is adjusted corresponding to the slip. Consequently following partial equation is going to be solved numerically:

$$\nabla x\left(\frac{1}{\mu(B)}\nabla xA\right) = -\sigma\dot{A} + J_{src} - \sigma\nabla V \tag{6}$$

Where J_{src} represents the applied current sources. The additional voltage gradient ∇V in 2-D field problems is constant over the conduction body. Strictly speaking the permeability μ should be constant for harmonic problems. However, FEM retains a nonlinear relationship in the harmonic formulation, allowing the program to approximate the effects of saturation on the phase and amplitude of the field distribution. FEM also allows for the inclusion of complex and frequency-dependant permeability in time harmonics. These features allow the program to model materials with thin laminations and approximately model hysteresis effects. Program is run at constant frequency f=50 Hz. In motor model is input only current in main stator winding while currents in short circuit coil and rotor winding are freely induced. For the transformer model current density is input in primary and secondary winding in all three phases and problem is analyzed at frequency 50 Hz.

3. Results from FEM

Three phase motor represents the standard motor construction which has symmetrical rotating electromagnetic filed due to three symmetrical phase windings, placed in stator slots having voltages and currents shifted with a phase of 120° between each other. Magnetic flux density distribution in machine cross section at no load is presented at Fig. 7 while in Fig.8 is presented distribution of magnetic flux density in machine air gap.

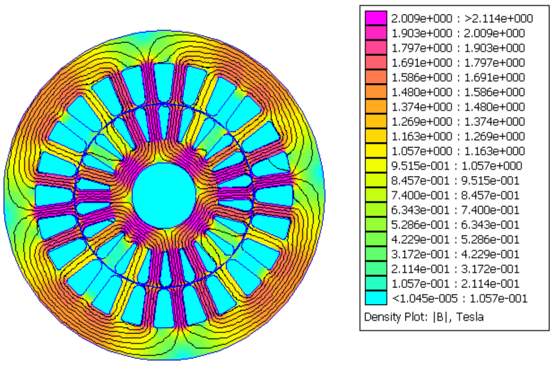


Fig. 7 *Magnetic flux distribution in three phase motor-no load.*

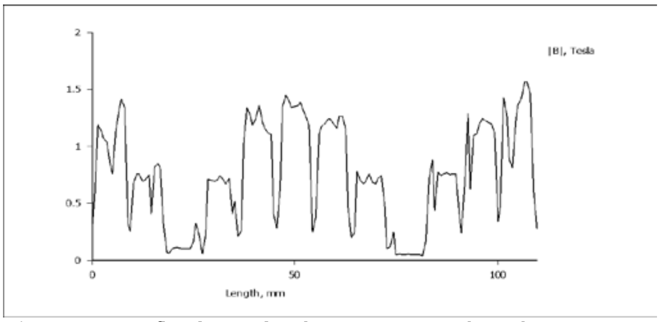


Fig. 8. Magnetic flux density distribution in air gap three phase motor at no-load

In contrast, single phase capacitor motor has an auxiliary element capacitor placed in auxiliary stator winding which enables motor start and enables rotating electromagnetic filed in machine air gap. In this specific case capacitor of 6 μF is placed in auxiliary winding and it is a permanent capacitor which stays in operation after motor start-up. Motor supply is from single phase network, but from its operating principle there are always two winding in stator of the motor (main and auxiliary) which are connected to voltage supply (Fig. 9). Magnetic flux density distribution in cross section of single phase motor at no load is presented at Fig. 10 while in Fig.11 is presented distribution of magnetic flux density in motor air gap.

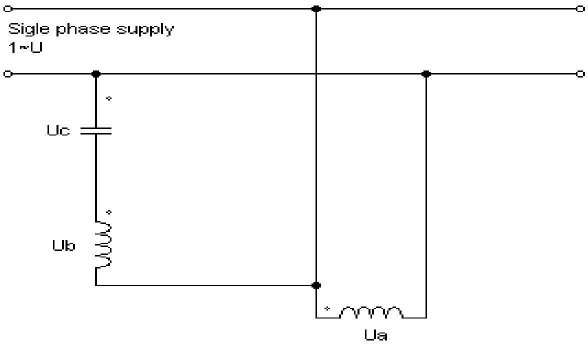


Fig. 9 *Electrical circuit of single phase capacitor motor*

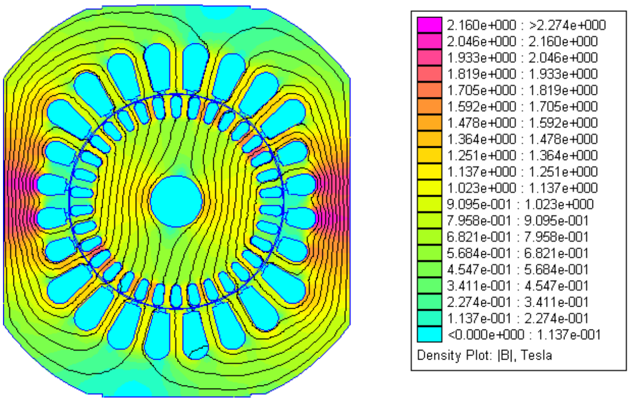


Fig. 10. *Magnetic flux distribution in single phase motor-no load.*

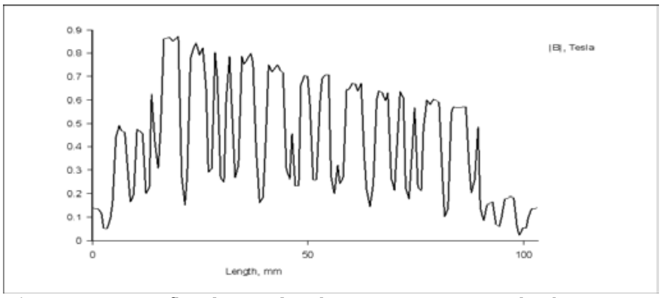


Fig. 11. *Magnetic flux density distribution in air gap single phase motor at no-load*

Three phase transformer represents the static electromechanical device i.e. there are no moving parts in machine construction. Electromagnetic field is symmetrical produced by three phase windings in primary winding coupled electromagnetically with secondary winding. Since there are no rotating parts in machine construction conductivity of material in secondary winding remains unchanged and same with the conductivity of primary winding. In no-load condition secondary winding is open, there is no current flowing, while primary winding is supplied with rated voltage. Magnetic flux distribution in machine cross section at no –load is presented in Fig 12 while distribution of magnetic flux density in first leg of transformer is presented in Fig. 13 and in second leg in Fig 14.

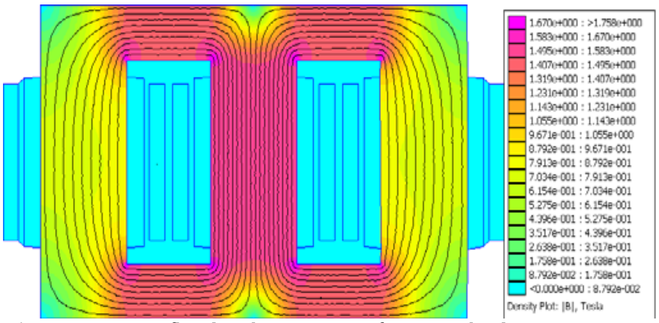


Fig. 12. *Magnetic flux distribution in transformer-no load.*

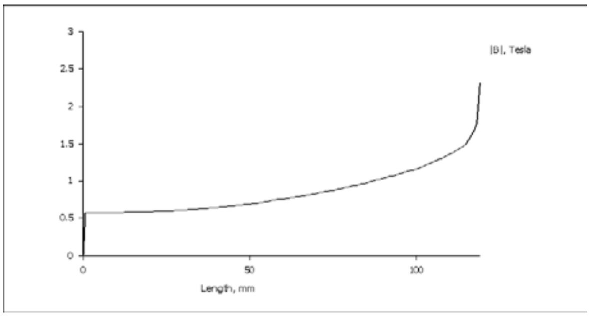


Fig. 13. *Magnetic flux density distribution in transformer first leg at no-load*

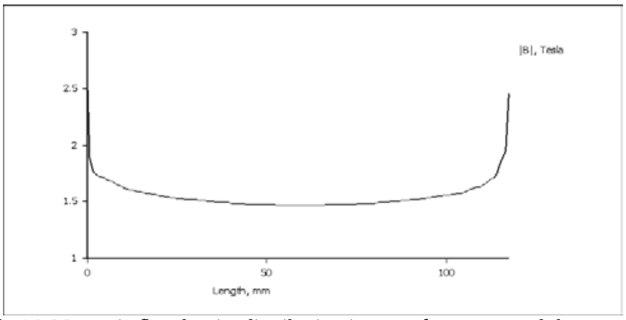


Fig.14. *Magnetic flux density distribution in transformer second leg at no-load*

In addition, rated load operating condition of machines is analyzed with respect to, magnetic flux distribution in machine cross-section as well as distribution of magnetic filed in certain parts of machine construction, subject to relation (3). For modeling the rated load operating conditions, appropriate densities of currents in stator windings for motors must be input while currents in rotor winding are induced and conductivity of rotor winding material is adjusted in correspondence to motor slip:

$$s = \frac{n_o - n_n}{n_o} \qquad (7)$$

where n_o is motor synchronous speed and n_n is motor rated speed.

For transformer rated load operating regime, rated load transformer currents are input in primary and secondary winding of transformer and problem is analyzed at frequency f=50 Hz. Magnetic flux distribution in all three machines is presented in Figs. 15, 16 and 17 respectively.

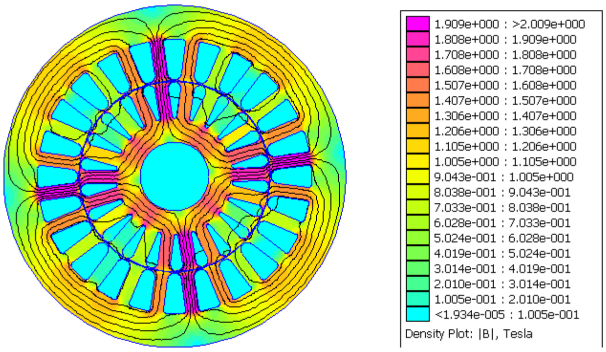


Fig. 15. *Magnetic flux distribution in three phase motor-rated load.*

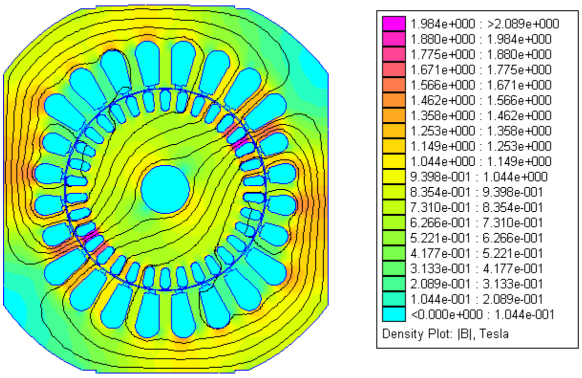


Fig. 16. *Magnetic flux distribution in single phase motor-rated load.*

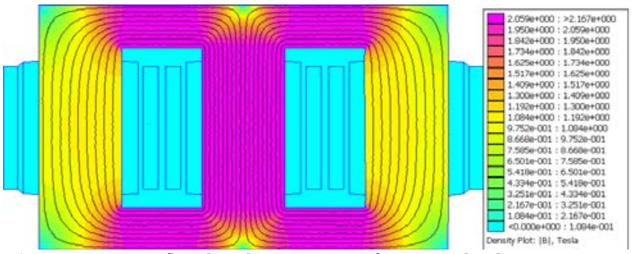


Fig. 17*. Magnetic flux distribution in transformer-no load.*

Magnetic filed distribution in air gap-H taking into account non-linearity of magnetic materials at rotating machines is presented in Figs. 18 and 19 for three phase motor and single phase respectively while for transformer in first leg and second leg in Fig. 20 and 21. First and second leg of three phase transformer differ in value of electromagnetic filed and flux density since second leg is always subject to higher values of flux density with respect to first and third leg of transformer core.

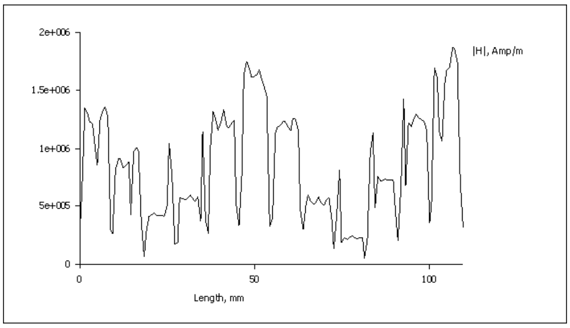


Fig. 18. *Magnetic flux distribution in three phase motor-rated load.*

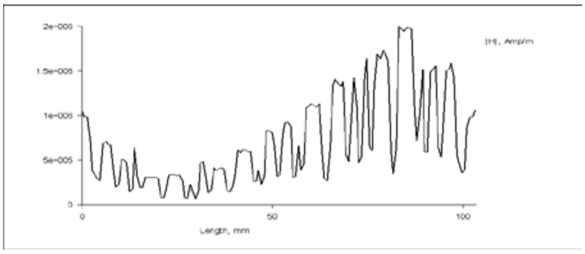


Fig. 19. *Magnetic field distribution in single phase motor-rated load.*

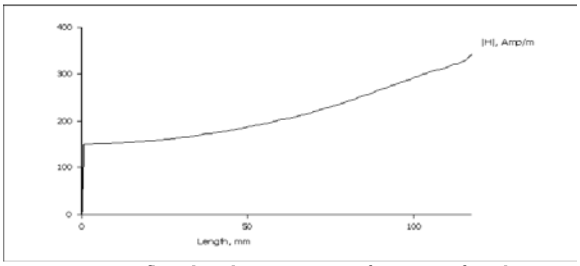


Fig. 20*. Magnetic flux distribution in transformer at first leg- rated load .*

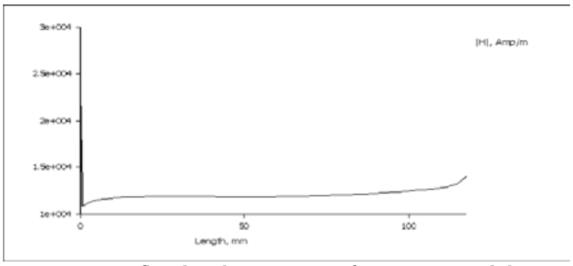


Fig. 21*. Magnetic flux distribution in transformer at second leg- rated load*

4. Conclusions

Numerical methods are widely used in calculation of electromagnetic fields inside electromechanical devices. Finite Element Method has received wide popularity in numerical solving the Maxwell set of equation which defines the magnetic flux density and electromagnetic field in every point of machine cross section. Calculation of above mentioned parameters is difficult to be done analytically due to nonlinearity of magnetic permeability of magnetic material implemented in construction of machines and they are often subject of assumption and implementation of figures based on practical experience. FEM can be implemented on any machine during the phase of designing and construction. In this paper FEM is implemented on three different machines from three different producers. Further more two of them are rotating electrical machines: three phase squirrel cage motor with symmetrical rotating electromagnetic field and single phase capacitor motor which is considered to be the more special case for modelling due to asymmetrical electromagnetic field in electrical machine and existence of capacitor in auxiliary winding. Three phase transformer is stationary electrical machine with symmetrical electromagnetic field. Magnetic field density distribution in all machines is obtained as well as electromagnetic filed for no-load and rated load operating regime. Further authors work will be focused on developing 3D FEM models of analyzed machines.

References

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