Steady State Performance Evaluation of a Permanent Magnet Synchronous Motor Based on FEA

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Abstract. The paper deals with the determination and an evaluation of steady state performance characteristics of a synchronous motor with surface mounted permanent magnets. At the beginning, a numerical calculation of the magnetic field distribution of permanent magnet synchronous motor (PMSM), under consideration is carried out. For this purpose, the Finite Element Method (FEM) is applied. By using output data from the field computation, all relevant characteristics of the motor are determined. The results of the numerical calculations are presented by diagrams. When possible, calculated steady state characteristics are compared with experimentally obtained ones; they show a very good agreement. An evaluation of the steady state behaviour of a permanent magnet synchronous motor, based on the Finite Element Analysis (FEA) is presented.

Key Words

Permanent Magnet Synchronous motor, FEM, FEA, Magnetic flux density, Coenergy, Electromagnetic torque.

1. Introduction

The 3-phase permanent magnet AC motor, acting as conventional synchronous type motor, has found renewed interest in the last two decades [1], [2]. The recent development of high energy magnets has enhanced their application in wide range of areas. The built-in of permanent magnets in the rotor core of synchronous motors as an excitation, and in particular the use of samarium-cobalt or neodymium-boron-iron magnets has challenged innovations in the permanent magnet synchronous motor (PMSM) design and analysis. In the paper, parameters and steady state performance characteristics of a PMSM are determined and analysed.

The main task is always to calculate steady state characteristics, as exact as possible. It has been found as rather complicated issue. It is obvious that the stress should be put on the exact determination of the parameters, as they are "playing" an important role in the accuracy with which all the characteristics of the PM synchronous motor under consideration will be derived.

2. Object of Study

The object of investigation is a Koncar motor type EKM 90M-6, with rated data: 18 A, 10 Nm, 1000 rpm. The motor is supplied from an AC source at 50 Hz, by current sine waves. Six permanent magnet poles made of SmCo5 are surface mounted on the rotor. The side view of the motor and its geometrical cross section are presented in Fig. 1 and Fig. 2, respectively.

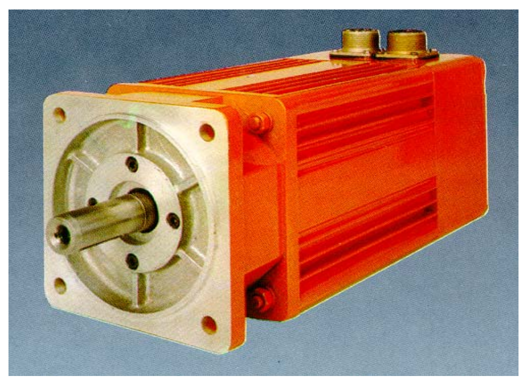


Fig. 1. Side view of a PMSM type EKM 90M-6

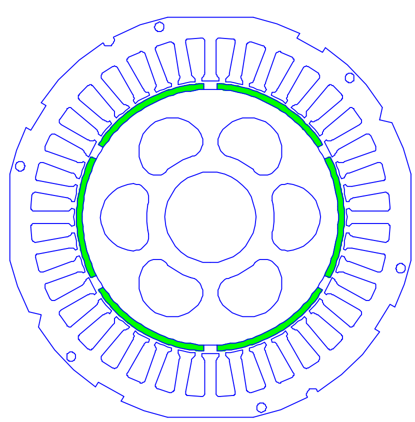


Fig. 2. Cross-section of the motor EKM 90M-6

3. FEM Calculation of PMSM

The Finite Element Method (FEM) has been used extensively in the numerical calculation of the magnetic field in electrical machines, in general. The output results, and a possibility to use them for calculation of both electromagnetic and electromechanical characteristics, are an excellent basis for carrying out Finite Element Analysis (FEA). Many researchers all over the world, including the authors of this paper, have done a lot of work in this area. Many papers in this topic have been published [3]-[11]. Different software packages exist in use. The presented results in the paper are computed by using an user friendly software package FEMM [12].

In the first step, usually considered as a pre-processing stage, depending on the user choice the mesh of finite elements with an appropriate density is generated fully automatically. In the FEA of the PMSM it is consisted of 17,190 nodes and 34,041 elements. For the purposes of FEM calculations of the magnetic field in the motor under consideration, the mesh is spread over the whole cross-section of the motor, as can be seen in Fig. 3.

In the pre-processor, named *femm.exe* all requested input data are included: • the exact geometrical cross section of stator and rotor magnetic core; • current density in the excited stator windings; • all boundary conditions of the region which is going to be analysed; • all material characteristics of the motor (permanent magnets, copper wire, B-H magnetising curve). The numerical FEM model of the PMSM, being completed, is ready for practical use.

When applying the software package FEMM for analysis of the permanent magnet synchronous motor, the magnetic problem is considered to be the time dependent harmonic problem. Hence, the calculations of the magnetic field are performed at rated frequency f_n=50Hz.

The field solutions are obtained by running the FEMM solver, called *fkern.exe*. As the whole cross section of the motor is used, only the first order Dirichlet's boundary conditions are applied; on the outer stator line and the inner rotor line it is set to be A=0.

Armature currents in the stator windings are varied from I=0 to the rated value I_n=18A. Rotor is freely moving (rotating) in the air-gap, continuously changing position, and the d-axis of the rotor is continuously taking different angles θ against the referential axis of the stator, firmly linked with one of the winding axes.

After the processing step is executed, the values of magnetic vector potential in every node of the motor domain are obtained. Later, one can use them for many purposes. The unit *femmview.exe* in the FEMM package is offering user friendly calculations and graphical presentations of the most important electromagnetic and electromechanical quantities.

A. Magnetic Field Distribution

The best way to understand the phenomena in any investigated motor is "to get inside and to see" the magnetic field distribution. Graphical presentation and visualization of the FEM results give the magnetic flux distribution in the cross-section of permanent magnet synchronous motor. A part of the most interesting results of the calculations are given in continuation.

The magnetic field distribution in PMSM is presented in Fig. 4, at following regimes: • (a) no-load condition, i.e. zero armature current, meaning magnetic field obtained by the permanent magnets only; • (b) rated-load with rated stator winding current I_n=18A and rated load angle $\delta_n=39^0$ [deg.el.], i.e. $\theta=13^0$ [deg.mech.]; • (c) loading condition at pull-out (maximum value) torque, meaning load angle $\delta_{max}=90^0$ [deg.el.], i.e. $\theta=30^0$ [deg.mech.].

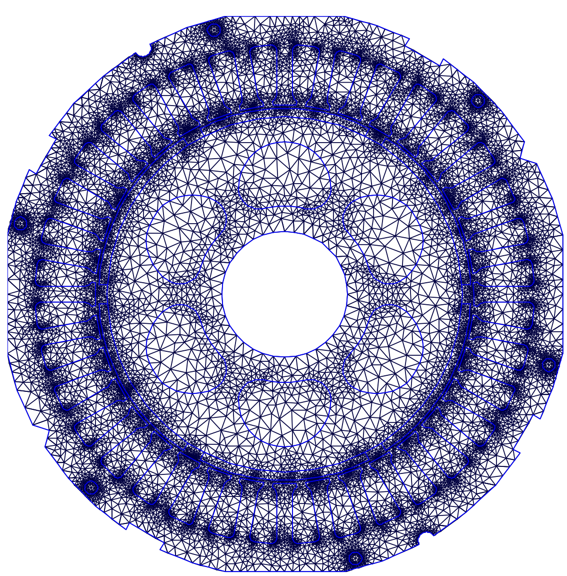
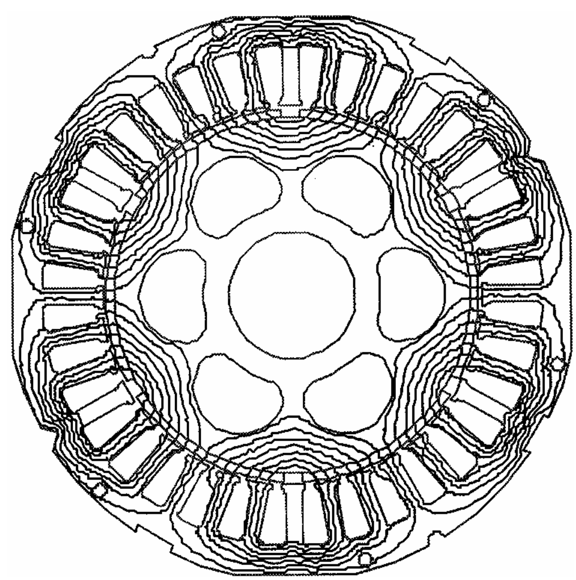
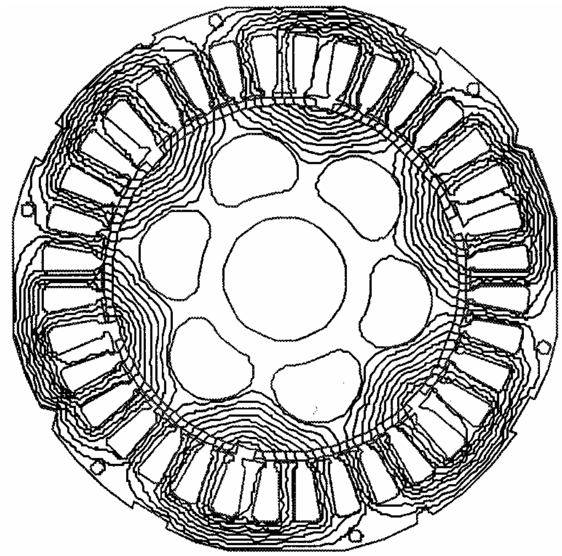


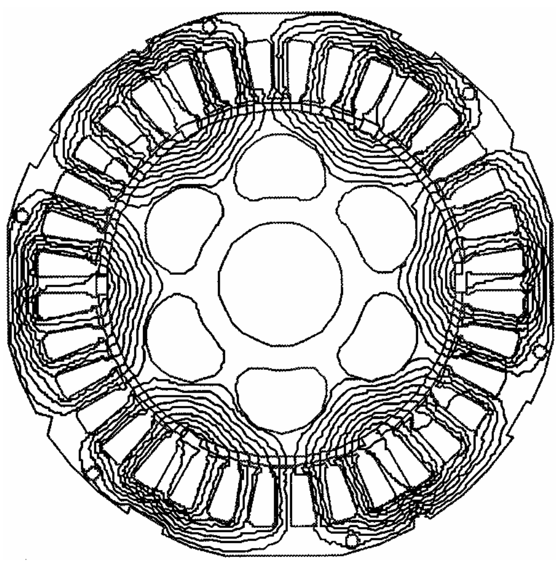
Fig. 3. Finite elements mesh of the PMSM



(a) no-load at I=0 and θ=0 deg.



(b) rated load at I_n=18 A and θ=13 deg.

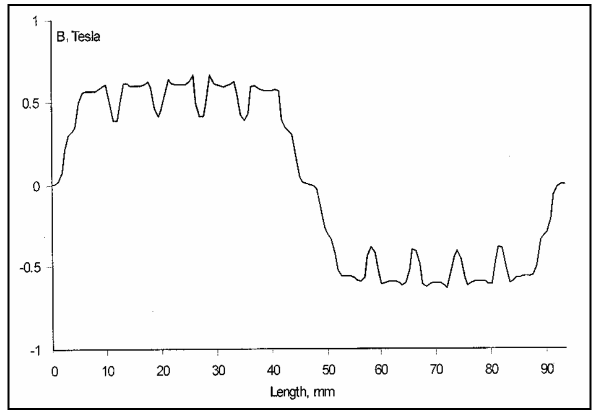


(b) pull-out load at I_n=18 A and θ=30 deg.

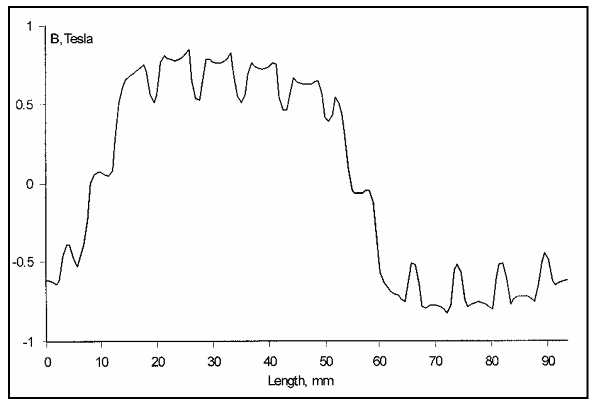
Fig. 4. Magnetic flux plots in the middle cross-section of PMSM under typical operating conditions

The FEMM software package enables comprehensive presentation of the spatial distribution of magnetic flux density along an arbitrary selected line, as well. The distribution along the mid-gap line is presented in Fig. 5 (a), (b) and (c), in the same way as precedent, at the same operating regimes and loading conditions of the PMSM. The following diagrams are spanned to one pole pitch.

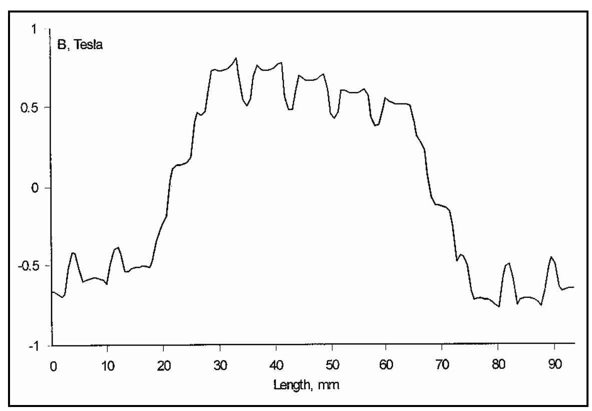
These diagrams can be used for carrying out a profound analysis of the air-gap magnetic field properties regarding both intensity and shape. When the permanent magnet synchronous motor is loaded, the influence of armature reaction magnetic field is clearly shown, in the figures. The influence of stator core teeth, on the air-gap field distribution is also clearly indicated in the figures.



(a) no-load at I=0 and θ=0 deg.



(b) rated load at I_n=18 A and θ=13 deg. (δ_n=39 deg.el.)



(c) pull-out load at I_n=18 A and θ=30 deg. (δ_{max}=90 deg.el.)

Fig. 5. Mid-gap magnetic flux density spatial distribution

B. Air-gap Flux Linkage

The numerical calculation of fluxes is based on the field theory, applied on a bounded and closed systems. If the calculations are performed per pair of excited poles, it is:

$$\Phi_g = \int_{\Sigma} \mathrm{rot}\boldsymbol{A}\cdot \mathrm{d}\boldsymbol{S} = \oint_{C} \boldsymbol{A}\cdot \mathrm{d}\,\boldsymbol{r} = \int_{\Sigma} \boldsymbol{B}\cdot \mathrm{d}\boldsymbol{S} \qquad (1)$$

For N excited turns, the air-gap flux linkage is:

$$\Psi_g = N \cdot \Phi_g = \iint_S (\boldsymbol{B} \cdot \boldsymbol{n}) \mathrm{d}S \tag{2}$$

C. Computation of Inductances

It is very important matter to calculate as accurate as possible the values of the parameters of the PMSM. Of the most important significance are the direct- and the quadrature- axis inductances, as they are determining corresponding synchronous reactances [13]; it is well known that they are the most significant parameters when dealing with steady state and/or dynamic performance analysis of PMSM.

The numerical calculation of inductances is based on FEM results. It is performed separately for d- and q- axis. In this case, it is found to be sufficient to calculate magnetic field only along one pole pitch. Neumann's boundary conditions of the second order, are imposed on the side lines of the cut [14].

The field should not be excited; it means that permanent magnets have to be replaced with finite elements related only with a correspondent permeability (μ_r=1.05), but not carrying the magnetic remanence (B_r=0.95 T). Only the armature winding is energized in an appropriate way [15], [16], as explained bellow:

1) d-axis: When calculating the direct axis inductance L_d, currents in the armature winding are distributed to peak at a quadrature axis, producing field with a peak at direct axis. The magnetic field distribution is presented in Fig. 6.

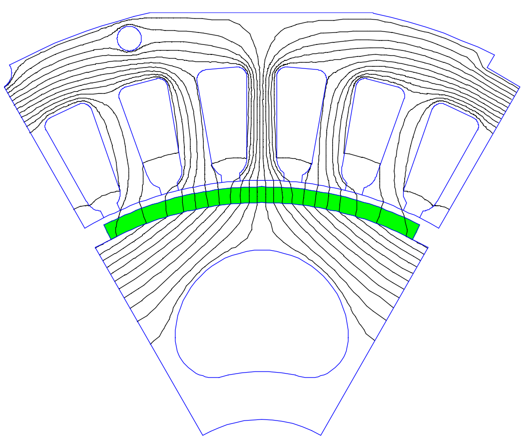


Fig. 6. Magnetic flux distribution for L_d calculation

2) q-axis: The quadrature axis inductance L_q, is calculated in similar way as L_d. In this case, the armature field is moved forward in space for 90^0el. and produces peak at a quadrature axis. It means that armature currents of the stator windings peak at the direct axis. In this case, the magnetic flux distribution for one pole pitch, and with the same boundary conditions when calculating d-axis magnetic field, is presented in Fig. 7.

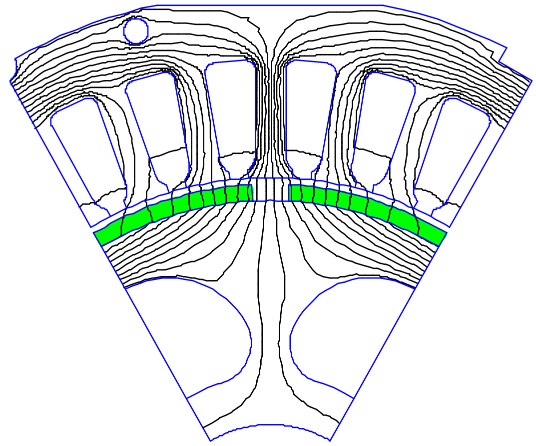


Fig. 7. Magnetic flux distribution for L_q calculation

In general, the inductance is calculated as a ratio of the flux linkage to the armature current, leading to:

$$L = \frac{\psi}{I} \tag{3}$$

The previous equation is applied for the computation of the d-axis and q-axis inductance. The corresponding flux linkage ψ, for each studied case is calculated by applying respective results FEM in Eq. (3); the magnetic field calculations are carried out in a way as previously has been explained, in accordance with Fig. 6 and Fig. 7.

As it was assumed the fictitious direct/quadrature winding to have the same number of turns as the real stator phase winding, it is requested to introduce another factor to find the direct- and quadrature- axis inductance, respectively [14]. For a 3-phase AC machine, the armature current in the direct/quadrature axis would have to be 3/2 times as great as the phase current to produce the same magneto-motive force along the respective axis as the three phase winding. Hence,

$$L_{d,q} = \frac{L}{3/2} \tag{4}$$

The calculations yield to results:

$$L_d = 5.816 \text{ mH} \quad \text{and} \quad L_q = 5.803 \text{ mH} \tag{5}$$

4. Motor Parameters Determination

The two-axes model of the synchronous machines is well established classical approach for an analytic-graphic investigation of their behaviour [13]. Many researchers widely use this method for fast prediction of the initial data for further more detailed and deepened analysis [17]. The basic idea is to develop and to use a set of equations, describing the motor performance in d,q reference frame and in terms of the loading angle δ. The only request is to have available the motor parameters. The accuracy, with which the performance characteristics of the PMSM will be determined, is in the direct dependence of the accuracy with which the motor parameters are calculated.

Some of the motor parameters could be easily measured; some are available from the producer's data; but very often their values are unknown, and it is requested an experience and skill to apply in the best way existing and well known numerical, experimental or analytical calculation methods. Different approaches are possible.

Starting with the numerical procedure, the *d,q* parameters of the PMSM under consideration are determined. By using the FEM results computed for L_d and L_q given in the previous heading with Eq. (5), one can determine the values for *d,q* reactance of PMSM, at 50 Hz as:

$$X_d = 1.827\ [\Omega] \qquad \text{and} \qquad X_q = 1.823\ [\Omega]$$

The already known fact that, that in synchronous motors with surface mounted permanent magnets, there is almost no difference between reactance along *d*- and *q*-axis has been also proved in this case.

Armature winding resistance R_a and a leakage inductance L_{sa} per phase are determined from an experimental testing investigation of the permanent magnet synchronous motor type EKM 90M-6 [2]. Their measured values are given bellow:

$$R_a = 0.1242\ [\Omega]$$

$$L_{sa} = 2.2\ [\text{mH}] \qquad \Rightarrow \qquad X_{sa} = 0.691\ [\Omega]$$

Having available the parameters of the PMSM, the phasor diagram at rated operating conditions is constructed [17], and is found the rated loading angle to be:

$$\delta_n = 39.2\ [\text{deg.el.}]$$

This value of the loading angle of the considered motor at rated operating conditions, will be determined by using numerical calculation of the steady-state characteristics via Finite Element Method.

5. Steady–State Characteristics

In the engineering practice, the intention of researchers, producers and users is always focussed to an estimation, analysis and evaluation of the electric machine behaviour. For that purpose, it is requested to have available performance characteristics, as accurate as possible.

The armature currents *I* and rotor positions θ along one pole pitch, are arbitrary selected. The rotation is supposeed to be counter clockwise. The reference axis is selected to be the *A*-phase axis of the stator windings; the initial rotor position and θ=0 deg. mech. is defined when stator *A*-axis and rotor *N*-pole axis (*d*-axis) are in accordance.

The PMSM is analysed at different operating conditions. Numerical calculations of the most relevant electromagnetic and electromechanical quantities, based on the FEM post-processing results, are presented in the following subsections.

A. Magnetic Flux Density

The flux density **B** is calculated from the basic relation used in the definition and introduction of the magnetic vector potential **A,** in the computations of the magnetic field with Finite Element Method. The equation defining the link between *A* and *B* is:

$$\nabla \times \mathbf{A} = \mathbf{B} \tag{6}$$

Applying the numerical procedure for its solution in the air-gap domain, magnetic flux density B_g per pair of poles is computed. In Fig. 8, characteristics of the flux density, for three typical armature currents *I* (zero, half of the rated and rated) and different rotor positions θ along one pole pitch (0–60 deg. mech.) of the motor are presented.

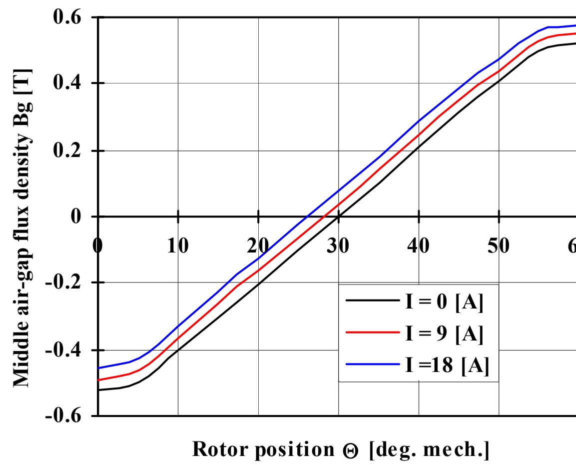


Fig. 8. Magnetic flux density characteristics $B_g = f(\theta, I)$

B. Magnetic Field Coenergy

In linear magnetic field problems, the magnetic energy *W* and the coenergy *W'* are equal. But, in the most cases, the problem is non-linear, so the coenergy is computed by using:

$$W' = \frac{1}{2}\int_V \mathbf{J}\cdot\mathbf{A}\ \mathrm{dV} \tag{7}$$

In fact, this quantity has no physical explanation, but it is very useful for calculation of the electro-magneto-mechanical quantities when an energy concept is applied.

For the quasi static model of the PMSM, electromagnetic coenergy *W'* is calculated numerically from the following expression:

$$W'(\theta, I) = \int_0^I \psi(I,\theta)\mathrm{d}I \,\Big|_{\theta=\text{const}} \tag{8}$$

The magnetic coenergy is calculated in dependence of the position of moving parts in the domain (the rotor) at arbitrary selected armature current. The calculated characteristics are presented in Fig. 9.

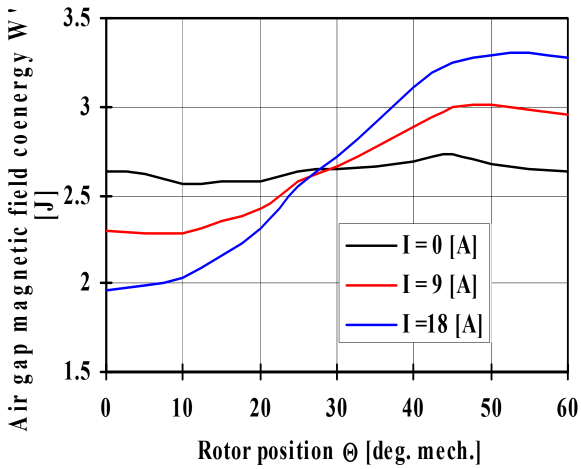


Fig. 9. Magnetic coenergy characteristics W' = f(θ,I)

C. Electromagnetic Torque

The knowledge of the static torque characteristics is very important issue for carrying out analysis and evaluation of behaviour of electric motors. For calculation, various approaches exist. In theory, the torque is computed from the field solution in a number of various ways. Three approaches for calculation are in practical use: Flux-Current Method, the Maxwell Stress Method and Virtual Work Method. In this paper, the energy concept for numerical calculation of torque in the PMSM is applied.

The electromagnetic torque T_{em} is effected by the variation of the magnetic field coenergy in the air-gap domain, at virtual displacement of the rotor, while the armature current is forced to be constant.

The equation for calculation is derived in the form:

$$T_{em}(\theta, I) = \frac{\partial W'(\theta, I)}{\partial \theta} \Big|_{I=\text{cons.}} \tag{9}$$

The results of calculations, performed for rated current I_n=18 A and $I_n/2$ =9 A, are presented in Fig. 10.

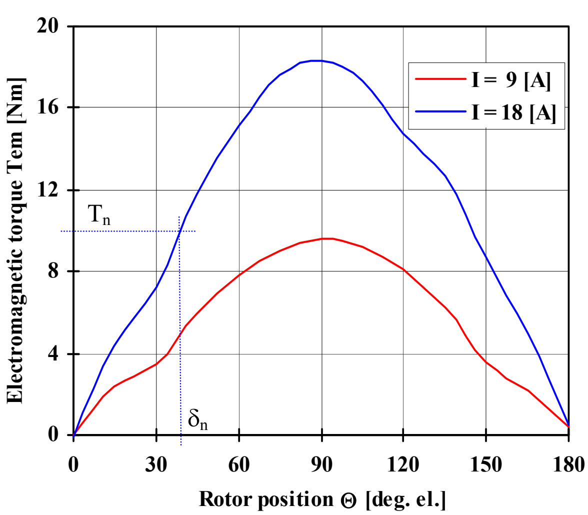


Fig. 10. Electromagnetic torque characteristics T_{em} = f(θ,I)

7. Performance Evaluation of PMSM

The proposed methodology by implementing different methods for calculation of steady-state characteristics under different operating conditions, enables to carry out a deepened performance analysis of the permanent magnet synchronous motor, and an evaluation of its behaviour at various loads.

The Finite Element Analysis (FEA), based on the computations performed by using FEM, enables to evaluate the magnetic field properties in the whole investigated domain of the PMSM. The Figures 5. where the spatial distribution of the magnetic flux density is presented are showing the effect of the armature reaction field on the main PM excitation field, in the most natural and evident way. The same phenomenon is also recognised in Fig. 8., presented by the points where the magnetic flux density characteristics B_g = f(θ,*I*) are passing through zero values.

The particular FEM calculation is performed, and the inductances, i.e. the reactances along the *d,q* axes are determined. By using them, the phasor diagram of the PMSM under rated operating conditions is constructed; the rated loading angle is found to be δ_n = 39.2 [deg.el.]. At the same time, the FEM results for the electromagnettic torque calculations, and the corresponding characteristics T_{em} = f(θ,*I*) presented in Figure 10., allow to determine numerically the rated loading angle, too. From the characteristic calculated at the rated armature current I_n=18 [A], for the rated value of torque T_{em}=10 [Nm] one can easy found almost the same value for δ_n=39 [deg.el.].

The performance characteristics of the considered PMSM are verified in two ways, depending on the available data. Some of the computed results are compared with the data obtained directly from the producer, and the others, with the experimentally obtained ones.

The armature windings' parameters are calculated in two ways: the resistance per phase R_a is calculated analytically; the leakage inductance L_{sa} per phase is determined by using three-dimensional magnetic field calculations in the whole investigated domain of the PMSM [2]. These parameters are also measured. Showing a very good agreement, they prove the applied methodologies as accurate and reliable.

As a verification of this work, here bellow is presented only a brief comparison of armature current *I*, at rated load torque 10 [Nm], determined by different methods:

Calculated: $I_{calc} = 18\,[\text{A}]$

Measured: $I_{meas} = 17.6\,[\text{A}]$

The above presented analysis is justifying the applied methodology for calculation performance characteristics of the PMSM type EKM 90M-6, as accurate and correct. Consequently, it can be recommended for similar calculations of any type of synchronous motors.

Conclusion

Finite Element Analysis is the best way for performance evaluation of the electrical machines in general. Presented approach, when applied on a surface mounted permanent magnet synchronous motor is proving the statement. Obviously, the phenomena outside of the magnetic core (i.e. end regions) are not showing an important influence, so the steady state characteristics, calculated by using Finite Element Method, in the 2D domain, are with the satisfactory accuracy.

This fact that the rated loading angle, determined with two different approaches is with the almost same value, is proving two important contributions presented in the paper: • first, the motor parameters calculated by FEM approach are quite accurate; • second, the use of the phasor diagram for determining the rated loading angle is proved to be correct. Knowing that the phasor diagram is drawn with FEM calculated values of the reactance X_d and X_d, the direct conclusion is that their values can be anticipated as accurate. On the other hand, the static electromagnetic torque characteristics are also determine-ed by using FEM, but in a quite different procedure. Both procedures giving the same results are obviously correct.

Measured values and the testing results are the best way to confirm both analytically and numerically calculated parameters and characteristics. The mutual agreement presented in the paper, is proving the proposed approach and methodology as accurate.

The authors are foreseeing the future task is transient performance and dynamic analysis of the considered PMSM. This work and in particular the presented results, showing an excellent agreement, can be used as good basis and relevant guide.

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