Optimization of Induction Motor by FE Analysis

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Abstract

The concept of FE model of induction (asynchronous) motor has been analyzed by author in [1]. While in [1] the analytical design [2] has been verified by numerical (finite element) analysis, this paper deals with optimization technique based on finite element solution. The aim of the optimization is to obtain the maximal possible torque. The optimization procedures, based on procedures successfully used by author with reluctance machinery [3], are transformed to spheres of induction machinery, where possible changes applied to model geometry and electric (supply current density and rotor bars current response) parameters are generating different mechanical torque on machine shaft. The induction machines are very often equipped in pumps and pump systems produced in industrial region in Tatabanya, Hungary.

Key words: Induction Motor; Finite Element Magnetic Field Analysis; Torque Computation; Optimization.

1. Introduction

The FE model of induction machine, used in wastewater (and other) pumps has been presented in [1]. The major attention has been paid to verification of analytical design approach presented by Kopylov in [2]. The verification was based on numerical analysis of the machine designed in [2]. The model of the designed machine has been built in FE environment and the flux density distribution in important parts of motor magnetic circuit has been verified (comparison numerical model results to analytical approach). The comparison has been based on flux density mean (average) values in the machine's air gap, stator and rotor yoke, stator and rotor teeth. In addition, the expected mechanical torque has also been verified by numerical (finite element) analysis.

Basic parameters of the machine are as follows:
output power P_2 = 15 kW,
synchronous speed n_1 = 1500 rpm,
rated voltage Un = 220/380 V,
rated stator current I_{1n} = 29 A,
number of turns in stator winding N_1 = 112.
stator winding current density J_1 = 5.91 MA/m^2.
external diameter of the machine stator D_e = 0.272 m,
internal diameter of the stator D = 0.185 m.
number of stator slots Q_1 = 48.
air gap width δ = 0.5 mm,
number of rotor slots Q_2 = 38,
external diameter of the rotor D_2 = 0.184 mm,
internal diameter of the rotor (shaft) Di = 60 mm.

Since the procedures, results, etc. should be repeated by any (financial) conditions, free available software package has been used to perform the analysis. Based on author's previous experience 2D model of the machine has been realized. Considering the available FE software the Finite Element Method Magnetics (FEMM) has been chosen to realize the FE analysis [4].

2. Torque Computation and Optimization Criteria

There are four suitable and well-known FE torque computation methods available:

- Maxwell Stress tensor method,
- Arkkio's Method (or Averaged Maxwell STM),
- Coenergy Method,
- Virtual Work method.

The comparison of these methods, their advantages and disadvantages are discussed e.g. in [5]. According to this discussion, the Maxwell Stress Tensor Method has been chosen to evaluate the torque for investigated induction machine. The torque T based on Maxwell Stresses is given by following equation:

$$T = \frac{1}{\mu_0} \iint_S \left(\vec{r} \times \vec{B}\right) \cdot \left(\vec{B} \times \vec{n}\right) - \frac{1}{2} B^2 \left(\vec{r} \times \vec{n}\right) dS \qquad (1)$$

where $\vec{r}$ and $\vec{n}$ represent the vector unit radial/normal to rotation axis. The formula represented by equation (1) can be rewritten for 2D task as the following line integral:

$$T = \frac{1}{\mu_0} \oint_{\Gamma} r B_t B_n \, d\Gamma \qquad (2)$$

with B_t and B_n as tangential and normal component of the flux density B at given point at the given path/line).

As can be seen in many papers, the correct evaluation of (2) may be very strongly influenced by jump of either tangential or normal component of the flux density. Therefore a special attention has been paid to meshing of the machine air gap to prevent the unwanted and coarse distribution of finite element nodes and elements. More detailed discussion on torque computation accuracy, comparison of methods, etc. can be seen in [5].

Following the described torque evaluation method an optimization criteria has been chosen. To be able to optimize the construction influence, current sources or used materials, the maximal possible torque is required to be obtained. The general aim of the optimization is better utilization of given volume, increasing the machine efficiency and so saving the input energy with keeping the machine outputs at the same level. The optimization procedures realized within this research are following the possible interferences into the model geometry (cooling system, technological requirements, position of the air gap) and/or size of input currents (both stator and rotor).

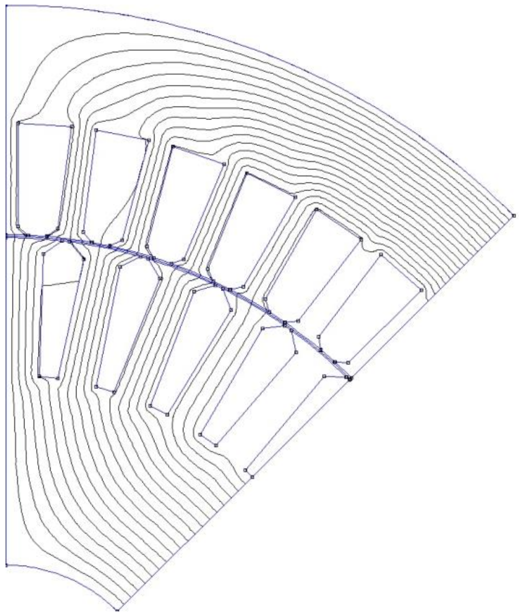

Fig. 1a. Flux Distribution in the Machine

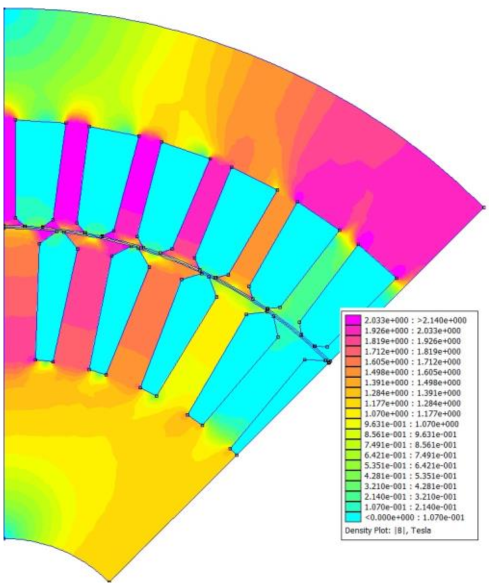

Fig. 1b. Flux Density Distribution in the Machine

3. Simulation Results

3.1. Influence of Technological Regions/Obstacles

While a “clear” (Fig. 1) model has been evaluated first (due to better conformity with analytical design), a necessary technological interventions must also be taken into account. Most frequently different cooling structures and systems can be used, as we as different binding and connecting techniques. All these influence the distribution of the flux density. Three different cases have been analyzed:

- interference into the magnetic circuit of the machine’s rotor,
- interference into the magnetic circuit of the machine’s stator,
- interference both into the magnetic circuit of the machine’s rotor and stator.

When technological obstacle is present in the flux path in machine’s rotor this causes the visible change of flux distribution; however, there is no significant change of the final mechanical torque. The situation is similar for obstacle in the flux path in machine’s stator – the flux and flux density distribution change can be observed (Fig. 2). This change of machine geometry lead to decrease of output torque by 3% (compared to originally obtained results). Since the field is rotating trough the complete magnetic circuit of the stator (rotor), there are not available tools to eliminate the above mentioned decrease. Of course, it can be minimized by decreasing the obstacle sizes. Generally, it can be said, that from the viewpoint of maximal possible torque, there is only minor influence of technological flux obstacles.

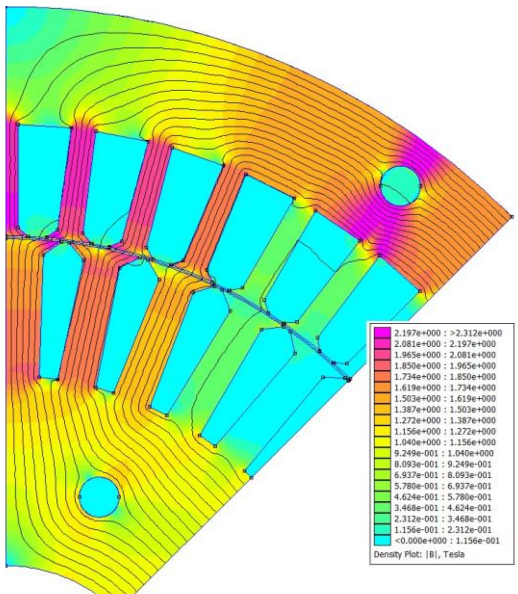

Fig. 2. Influence of Technological Elements on Flux Density Distribution

3.2. Influence of the Supply Current Size

This criterion is one of the most important for reluctance drives. The change of obtained results is not so significant when applying this to induction machinery; nevertheless, a meaningful consequence can also be observed. The basic idea of this procedure is in evaluating the response of the machine's magnetic circuit. Based on used material characteristics (see B-H curve, Fig. 3) there are parts of the circuit with overload of flux density and there are part with low magnetic load. The most important is the balance with these two parts – and this cannot be evaluated analytically. Of course, the balance is strongly dependent on used material, size of over- and under-loaded area and size of the load itself. Therefore different current supply schemes (values) have been analyzed by finite elements – from 5% to 800% (1600%) of rated current (the thermal losses and the winding current conducting capacity has not been taken into account). The results can be seen in Table 1, where 100% is assigned to rated supply current.

Table 1. Current Supply Influence on Machine Torque

Size of Current Supply (% of I_n)	Torque (Nm/m*)	Torque (%)
5	0.1	0.2
10	0.5	0.7
25	12.0	16.0
50	33.0	45.0
100	73.0	100.0
125	92.0	127.0
200	138.0	190.0
400	229.0	315.0
800	340.0	468.0

*for 2D model the units of torque are obtained in Nm per 1 m of model axial length.

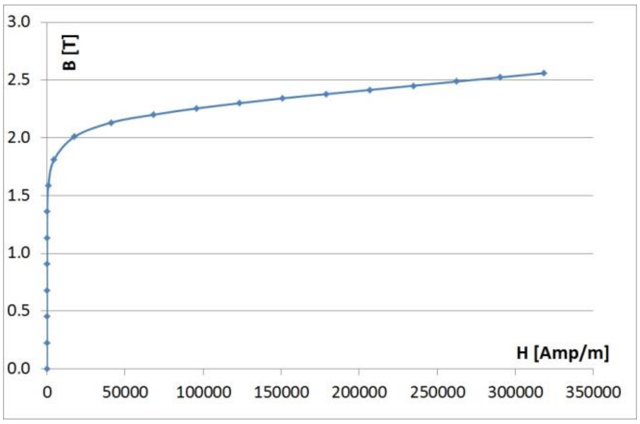

Fig. 3. Used Material B-H Curve

The results presented in Table 1 can also be seen in Fig. 4. Logarithmical scaling factor for y-axis has been used to demonstrate the influence of supply current size while percentage of rated current I_n is represented on x-axis. Compared to reluctance machines, where the geometry and the used material parameters have the major influence on machine torque, the Lorentz forces, resp. forces between current conducting wires are dominating. Therefore the influence of geometry or material change in this case is not so fundamental; nevertheless, it is still visible and important. The effect of used material can be seen in torque vs. supply current characteristics (Fig. 4). There is a significant response of the system to supply current increase – rapid increase of the mechanical torque at the beginning of the characteristics. The absolute increase is slowly reduced by higher values of current supply; however, the reasonable response of the system can be observed till 125% of rated current. So it can be said, that the system of supply windings and the magnetic circuit of the machine does not match together – there is about 25% reserve in supply current. On the other hand, it also can be stated that the magnetic circuit of the machine will be loaded by optimal load when 125% of rated supply current will be used.

3.3. Influence of the Air Gap Radius

From Fig.1a and Fig. 1b it can be seen, that there is an asymmetry in stator and rotor flux density distribution. Therefore, due to unification of maximal magnetic load, a radius of the air gap (two new positions analyzed) should be changed – without changing the outer sizes of the machine and without changing the air gap width itself. These changes have been realized for two different current supply cases:

a, with same size of current density, and

b, with same size of supply current.

The changes due to this logic are not positively influence the machine torque. The machine torque drops down to 77% (81% for second different air gap radius) when current density at the same level or to 94% (96%) when the absolute value of current supply used. It can be said, that balance of the flux load between machine's stator and rotor will not lead to required torque decrease. This is caused by interaction between stator and rotor currents on the one hand, and the radius of these forces activity.

4. Conclusions

At the end of this step of induction (asynchronous) machine analysis the following can be concluded:

- the analytical approach and design has been successfully verified by means of finite element technique [1], where magnetic load of machine parts has been analyzed, as well as mechanical torque computed;
- based on the verified model the torque optimization in FE environment has been realized. Maxwell Stress Tensor Method has been used to evaluate the machine torque;

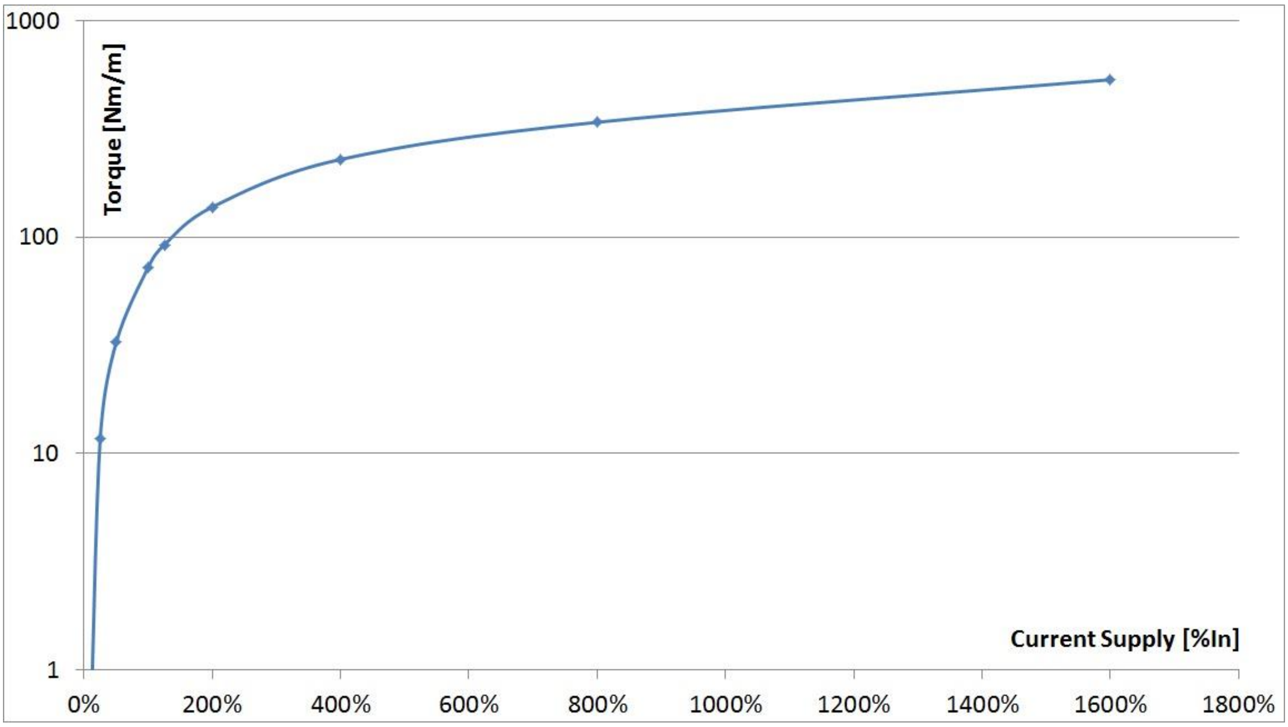

Fig. 4. Torque vs. Current Supply Characteristics

- influence of different technological magnetic flux obstacles (cooling system, technological and mounting slots) has been analyzed with partial conclusion – these non-uniformities in machines' magnetic circuit have only minor influence on machine output torque;
- the most important part of the machine optimization is the analysis of current supply size. Due to magnetic circuit load, the output torque increases by increasing the input current size(s). Nevertheless, there is a significant change in torque vs. current characteristics – this occurs at cca 125% of rated current, so it can be said, that the supply system and the machine magnetic circuit are not balanced. The best results and maximal efficiency will be reached for higher supply current as originally designed. Either the supply system is undersized or machine's magnetic circuit oversized;
- the influence of air gap radius, reps. balance between magnetic load of machine's stator and rotor has also been analyzed. Because of the stator and rotor currents interaction on given radius, this change leads to unwanted and unacceptable decrease of machine torque.

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