# FE Model of Induction Motor

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**Abstract**

Based on local situation in the industrial region of Tatabanya, Hungary, the most frequently used mechatronical actuator has been identified. Wastewater and/or other pumps, as well as scuba pump systems are mostly equipped by induction (asynchronous) motors. This machinery often meets the major production of the largest local company, as well as a lot of other smaller corporations dealing with electrical machinery and mechatronical actuators. The numerical analysis of the machine, presented in the paper, is a base for following optimization processes. The main objective of this work is to optimize the used machinery with special attention paid to motor's torque and so to save the energy necessary to power the used technologies (the optimization procedures and the following results will be presented in author's next paper).

*Key words*: Electrical machines; Induction Motors; Finite Element Field Simulation; Numerical Analysis; Comparison of Analytical Design and Numerical Analysis.

## 1. Introduction

Nowadays, a major attention is paid to environment-friendly technologies and equipment. The large amount of money (and research time) is invested into a "green" energy, which, unfortunately, could lead to local damages of the countryside and even more expensive products for both households and industry (including the sector of transportation). There is another field to improve the human-nature balance – the energy saving and economization. According to [1], almost all electricity is generated by rotating electrical generators, and approximately half of it is used to drive electrical motors. The key challenges to increased efficiency in systems driven by electrical machines lie in three areas: to extend the application of variable-speed electric drives into new areas through reduction of power electronic and control costs; to integrate the drive and the driven load to maximize system efficiency; and to increase the efficiency of the electrical drive itself (work of B. C. Mecrow and A. G. Jack in [1]).

This paper is based on the third issue from the list - higher efficiency of the electric machinery. The electrical machinery (electromechanical actuators) is not a negligible part of the line. Based on work of De Keulenaer, H., et al. (2004, Energy-efficientmotor-drivensystems, EU-sponsored programme, European Copper Institute, Brussels) by switching to energy efficient motor systems, EU industry would save 202 billion kWh in electricity consumption (approximately 7.5% of overall consumption) and 5.6 – 8 billion Euro per year (operating costs and environmental costs).

The industrial market sector for fixed-speed machines is completely dominated by the induction motor, whose efficiency typically ranges from 76.2% at 1.1 kW to 93.9% at 90kW (European Commission Joint Research Centre on Electric Motor Efficiency, 2004). Other market sectors, such as white goods, power tools, etc. mainly utilize smaller, commutator machines, whose efficiency is typically 50% or less (B. C. Mecrow and A. G. Jack in [1]). Generally, the efficiency of the machinery (ratio between the useful energy and input energy) is usually between several tens (40-60) of percent to 90-98%, in reciprocal proportion to the machinery size. Unfortunately, the "small" (and low efficiency) machinery is still more and more equipped in the modern cars, fridges, washing machines, robotic systems and/or many more industrial applications. The main idea of the problems solved within the frames of the author's research program is the optimization of this machinery. Realizing (sometimes even the smallest) changes e.g. in machine construction might lead to relatively large response in efficiency, either positive or negative. These changes are very difficult to predict by analytical methods (because of the complexity of the problem – geometry of the machinery, type of power supply, different boundary conditions, etc.). It is also impossible to verify all these changes by measuring the machinery in the laboratories (price of lab-time and equipment, price of prototype realization, etc.). The solution is in application of numerical methods which are able to solve the electrical and mechanical problems with acceptable inaccuracies. Generally, there are three base principles which can be used for proposed solution – the Finite Difference Method (the simplest and the oldest), Boundary Element Method (the most complicated) and the Finite Element Method. The latest one will be used in this research program, as the applicant's experience and know-how (in compliance with general knowledge and opinion of experts) is based in this area. One of the goals of the project is to evaluate the mechanical properties of the machinery according to the electrical and electromagnetic field solutions.

Two major objectives are presented in this paper. The FE model of the induction machine is introduced to the reader and the analytical design of the machine (based on work of I. P. Kopylov in [2]) is verified by numerical technique (Finite Elements model).

## 2. Induction Motor Model in FE

There are several significant problems and singularities when building a model of an induction machine in FE environment. The main difference compared to other rotational machinery is that the current frequency in rotor windings generally differs from frequency of the stator power supply. Other complicated task to solve is the current distribution in rotor windings. The same goes for squirrel caged machines. The problems of induction motors FE model are presented e.g. in [3-5]. Transient FEM analysis is realized in [3] while the 2D FE model is couplet with external circuit elements. Nevertheless, the authors recommend determining the external circuit parameter more precisely to obtain better agreement between measurement and simulation. The transient analysis (realized in OPERA 2D – AC solver) has been done in [4]. The influence of rotor slots of different geometry has been studied and discussed in the paper where the machine torque and its efficiency are the most important parameters. Resources similar to [3] have been used in [5]: the end winding of the stator and the rotor were described in the circuit model, while the body part was done in the field model. In each moment, the analysis is solved by combining external circuit equations with the electromagnetic field equations.

Different approach (similar to author's previous work [6]) has been chosen to analyze the magnetic field distribution in the presented paper. The important parameters are given either from prescribed conditions or from analytical approach based on work of I. P. Kopylov [2].

## 3. Problem Solution

As mentioned above, the process of problem definition and solution presented in this paper can be generalized in the following:

- motor design based on given input parameters (as type, geometry, dimensions, etc.),
- determination of parameters necessary to FE analysis realization,
- realization of FE model,
- comparison of analytical design results and FE analysis.

These four bases of the presented research are described in the following chapters.

### *3.1. Motor Design and Determination of Important Parameters*

A typical example of the induction machinery has been used. This machine is presented e. g. in [2] and is designed as a squirrel cage induction machine with output power $P_2$ = 15 kW, synchronous speed $n_1$ = 1500 rpm, rated voltage $U_n$ = 220/380 V, rated stator current $I_{1N}$ = 29 A, number of turns in stator winding $N_1$ = 112. These parameters, together with slot geometry and sizes, will lead to stator winding current density $J_1$ = 5.91 MA/m$^2$.

The major dimensions of the machine are based on analytical design, resp. external (customer) requirements. 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.

The air gap width $\delta$ is required to be equal to 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) $D_i$ = 60 mm.

Current in the rotor bar is determined according to [1]:

$$I_t = k_i I_1 p_i \tag{1}$$

where $k_i$ is a parameter based on magnetisation current influence and windings resistance influence on ratio between $I_1$ and $I_2$. Its value can be assigned from function $k_i$ = f(cos(φ)) published in [2]. Current reduction factor $p_i$ (for squirrel caged rotors) can be obtained from the following:

$$p_i = \frac{m_1 N_1 k_{v1}}{m_2 N_2 k_{v2}} \tag{2}$$

Taking the all necessary data into account, the following value for $I_t$ is obtained:

$$I_t = 0.9 \cdot 29 \cdot 16.94 = 442A$$

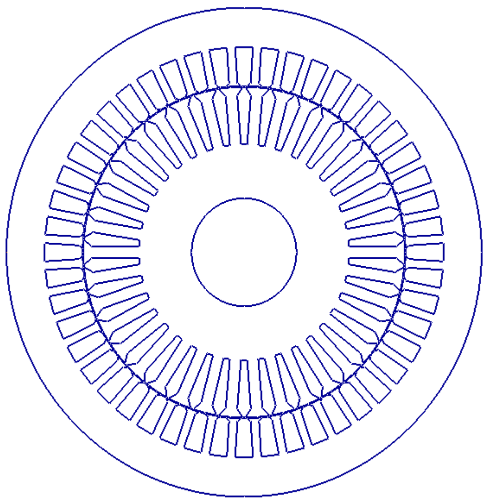

Fig. 1. Cross-section of the Machine

The current distribution in concrete bar is given by motor (stator) winging design (number of poles) and given number of rotor bars (38). The maximal current density in rotor bars is then $J_2 = 2.5$ MA/m$^2$. The designed machine cross-section can be seen in Fig. 1. Although the rotor current density along the rotor's perimeter has not a strictly sinusoidal shape, sinusoidal distribution has been assumed in the presented process.

### *3.2. Realization of FE Model*

Different FE software environments had been considered to realize the model of the described machine. Based on the project proposal (see acknowledgement) only free available software packages could be used. The disadvantage of this solution is, of course, the lack of some additional functions (as mathematical operation on obtained results); nevertheless, the free FE software is nowadays obtaining a user friendly environment, powerful preprocessor, a set of integrated mathematical functions (as integration or derivations), and, what is very important for future optimization processes, unlimited number of elements and nodes in 2D. Therefore, the Finite Element Method Magnetics (FEMM) has been chosen to realize the FE analysis [7].

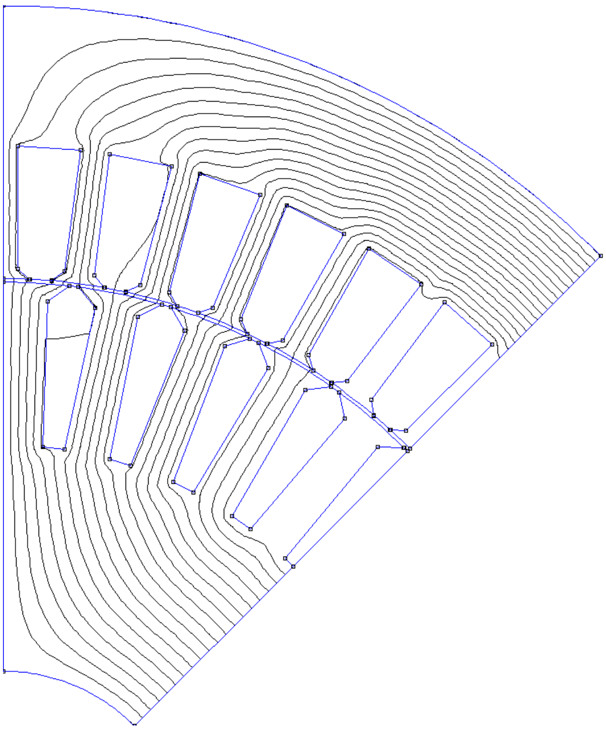

Fig. 2. Magnetic Potential Distribution

The complete model has more than 118.000 nodes. Because of the symmetry and boundary conditions precise and accurate results could be obtained for 1/8 of the machine. This segment contains less than 15.000 nodes and the computation time for non-linear analysis takes several tens of seconds.

The basic outputs of the FE model (for rated load condition) can be seen in Fig. 2 (magnetic flux (magnetic potential) distribution) and Fig. 3 (flux density distribution). One of the most important factors, especially when investigating the magnetic load and mechanical parameters of the machine, is the flux density distribution in the air-gap. More detailed description of available procedures, requirements on FE mesh, advantages and disadvantages can be seen in [8]. The mentioned characteristics for presented example can be seen in Fig. 4.

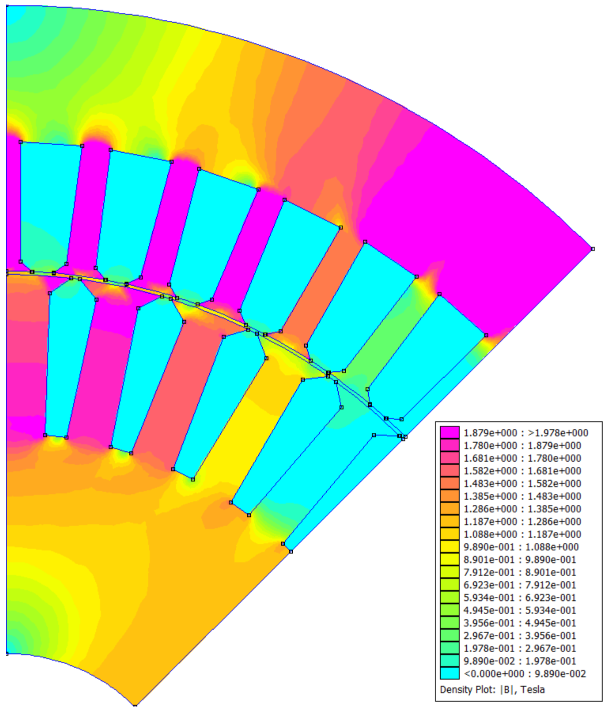


Fig. 3. Flux Density Distribution

### *3.3. Comparison of Analytical Design Results and FE Analysis*

The analytical approach is very precisely described in [2]. Based on prescribed technique and procedures, the expected flux density is compared to ones obtained by FE analysis. While the analytical process lead to a unique number, representing the value of flux density in the complete part of the machine (e. g. yoke, teeth, air gap, etc.), the results obtained by finite elements are understood as distributions in the 2D cross-section of the machine. Therefore a path through the most loaded parts of teeth is defined and the average value is calculated to be able to realize the comparison. Where possible (e. g. stator and rotor yoke, air-gap) the path defined by analytical procedure is also followed in finite elements. Based on this comparison (see table 1) it can be stated that the analytical approach presented by I. P. Kopylov in [2] and the finite element analysis lead to almost same results. There is practically no significant difference in expected value of the flux density

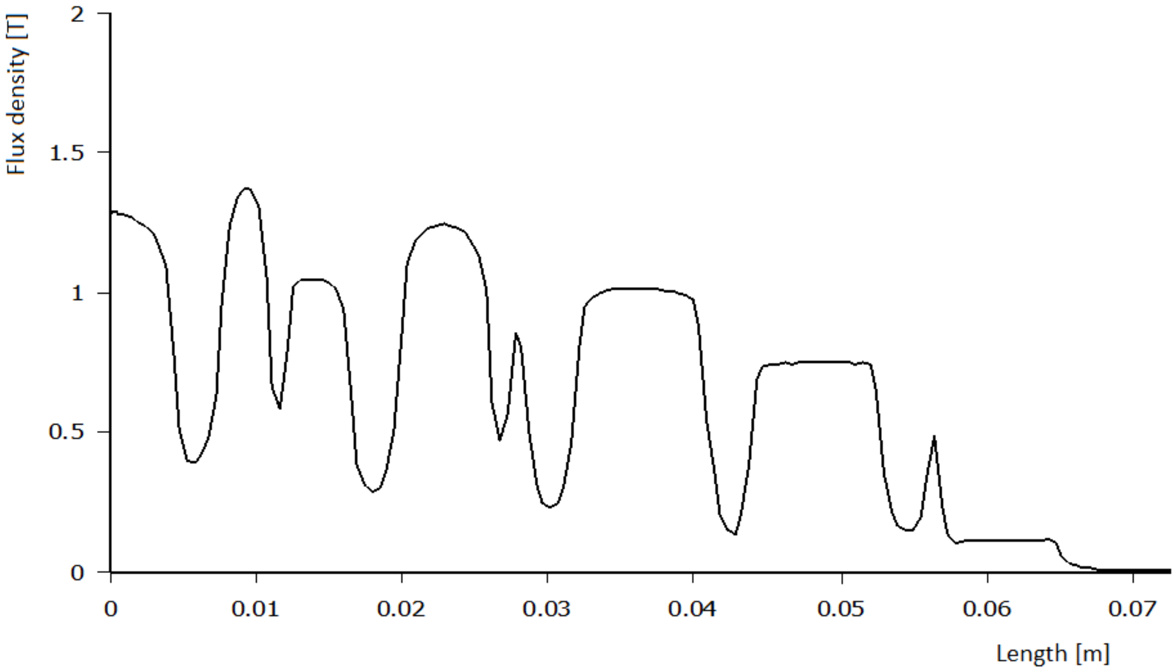


Fig. 4. Flux Density in the Machine Air-Gap

in the air gap. Very good agreement is obtained for flux density in stator yoke and rotor teeth; a relatively large difference is observed for stator teeth (+13%) and rotor yoke (+20%); however, the FE flux density in machine teeth is evaluated for the most loaded axial path in the most loaded tooth. Therefore the results might be higher as from analytical approach. It also must be stated that the values presented in table 1 are valid for rated slip (s = 0.0261) of the machine leading to speed n ≈ 1460 rpm.

Table 1. Flux Density in the Machine

| Description | Flux density [T] by analytical approach | Flux density [T] by finite elements |
|---|---|---|
| Air gap | 0.776 | 0.75 |
| Stator yoke | 1.65 | (2.25-2.00) average: 1.58 |
| Rotor yoke | 0.95 | (1.17-1.23) average: 1.2 |
| Stator teeth | 1.95 | (2.19-2.28) |
| Rotor teeth | 1.805 | 1.88 |

Despite of very high agreement between analytical and numerical analysis there is a relatively large discrepancy in machine torque. While the analytical approach lead to rated torque T = 95 Nm (number of poles p = 2, frequency f = 50, slip s = 0.0231, rated power through the air gap $P_\delta$ = 14960 W), the numerical analysis gives 72 Nm. This is caused by constant phase shift between the stator and rotor magnetic field, which may vary according to the machine construction and operating parameters. This parameter will be taken into account in the following optimization processes. Due to the good agreement of the other results the presented model and used techniques will be used for upcoming optimization processes.

## 4. Conclusion

The analysis of the local situation in area of industrial demands on electromechanical (mechatronic) actuators in region of Tatabanya, Hungary, has been realized. As the significant part of the local industry production is connected to pump systems equipped with induction machine, these machinery has been identified as the most actual target of the research.

This paper presents the first results from project focused on induction motors optimization. The contents of this paper can be summarized and concluded into the following:

- The necessity of machine optimization and efficiency increase has been demonstrated in the introduction. This has been realized by brief literature retrieval, mostly cited from [1].
- Analytic design of the machine has been realized. This procedure is realized according to practices of I. P. Kopylov published in [2].
- The possible problems of induction machinery FE modeling have been presented and discussed [3, 4, 5]. An alternative solution focused on analytical design has been given.
- The FE software environment has been analyzed, with special attention paid to free available software, and a concrete software product has been chosen [6].

- The FE model of designed machine has been realized and evaluated.
- The results based on FE analysis have been compared to ones based on analytical design. A very high level of agreement and conformity can be stated.

The presented results are considered as an input date for optimization processes. These will be realized by author in the close future and will be presented in the following paper.


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