# FINITE ELEMENT ANALYSIS OF HIGH SPEED INDUCTION MOTOR WITH AXIALLY SLITTED ROTOR

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**Abstract**: This paper deals with an analysis of three phase, two pole high speed induction machine with axially slitted solid rotor. The finite element model of induction motor with axial slits has been developed and motor has been analyzed for several slips in order to get performance characteristics. Setting the simulation is crucial and will be discussed. All-important fields and performance characteristics are presented.

**Keywords**: high-speed, induction motor, solid rotor, finite element method

## 1. INTRODUCTION

Nowadays, high-speed solid rotor motors have found its place in the market. In order to boost power density or reduce gear boxes, high speed motors supply from frequency inverter are used. Increasing shaft rotating speed by higher input supply frequency leads to better shaft power with the same active motor volume [4]. Unfortunately, increasing shaft rotating speed brings motor to a certain limitation. Mechanical limitation is caused by centrifugal force and therefore solid rotor, made of one piece of steel is used. There are several feature modification in rotor construction, see Fig. 1. Very popular modification is copper coated rotor (see. Fig 1a), where the rotor yoke is coated with thin layer of copper or other high conductivity material. Our subject of interest is axially slitted solid rotor (see Fig. 1c). Solid rotors, especially smooth (see Fig. 1b), are characterized with low power factor and great eddy currents losses due higher harmonics. There are several ways how to reduce these harmonics. One of them is increasing the air gap or use a ferromagnetic wedges with small relative permeability [1].

Unlike classical induction motor, smooth solid rotor cannot be analyzed classical numerical method due to separated electrical and magnetical path. Calculation method describe in [1] is called multilayer transfer matrix (MLTM) method, where the idea is that the transfer matrix calculates the strength of the field in each thin metal layer from the center to the surface of the rotor. Smooth solid rotor (Fig. 1b) can be easily analyzed with finite element approach, but it takes a lot of time to determine the working characteristics. It was shown in many studies [1], [4] and [5] that magnetic flux, due to magnetic skin effect, do not penetrate very deep towards the center of the rotor. Current density is mostly concentrated on the surface as well. Therefore, this concept has a large rotor resistance and need a great slip to produce required torque.

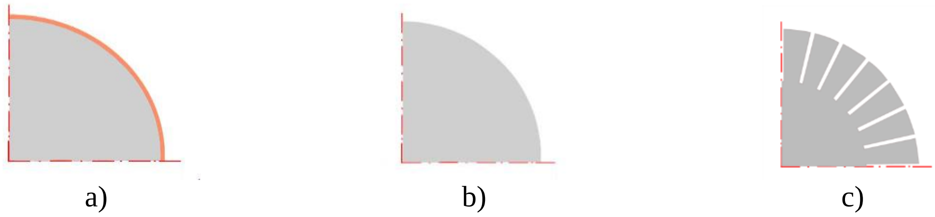

a) b) c)

**Figure 1:** Solid rotor topologies: (a) Coated solid rotor, (b) smooth solid rotor, (c) slitted solid rotor

One way, how to improve efficiency is by slitting rotor surface in axial direction. This method will cause better penetration of magnetic flux and electrical current density. The depth of the slits should be choose wisely with respect to mechanical toughness at the bottom of the rotor teeth. As a matter of fact, the depth of the slit is trade-off between electromagnetic and mechanical design [2], [4]. The width of the slits is important as well. The narrower slit is, the less saturated teeth will be and better performance can be obtained.

## 2. SIMULATION OF HIGH SPEED INDUCTION MOTOR

Presented motor have 24 stator slots and 28 rotor teeth. Material with label M235-35A was used for stator sheets and its BH curve for frequency $f$ =1 kHz and $f$ =500 Hz was defined from datasheet up to $B$ =1.3 T. Rotor is made of one piece of steel, labeled S355J2G3. BH curve of rotor steel was measured at the low frequency of 15 *Hz*. The steel conductivity $\sigma$ =2.72 MS/m at temperature 150 *°C*, was defined in model. Main design and rated parameters are presented in table 1.

| Machine rated and design parameters | Value | Unit |
|---|---|---|
| Line to line voltage | 400 | [V] |
| Rated power | 12 000 | [W] |
| Air gap length | 1 | [mm] |
| Rated frequency | 750 | [Hz] |
| Number of stator slots/rotor slits | 24/28 | [-] |
| Stator outer/bore diametr | 120/65 | [mm] |
| Width/depth of rotor slit | 1/12 | [mm] |
| Rotor stack & one steel end ring length | 80 & 35 | [mm] |

**Table 1:** Main Motor parameters

Mesh and sampling time are very important aspects. Mesh and sampling time have to be in balance between computing time and accuracy. Motor is supply by frequency of $f$ = 750 Hz. Our sampling time, to provide sufficient results, was set to be $T_s$ = 2.66 μs. The sampling time was set intentionally to make $N$ = 500 samples during one period and include higher harmonics. The mesh was dense in area of air gap and motor was analyzed with more than 40000 mesh elements.

### 2.1. END-EFFECT CORRECTION FACTOR

Rotor modification by axial slits leads to better performance. The assumption is that all electrical current conduct in the teeth and therefore resistance and leakage inductance of the rotor end rings is extra calculated and added in the model. The resistance $R_{kn}$ between two teeth is calculate by follow equation.

$$R_{kn} = \rho_{Fe150} \cdot \frac{\pi \cdot D_{kn}}{Q_2 \cdot S_{kn}} = \frac{1}{2.88 \cdot 10^{6}} \cdot \frac{\pi \cdot 51 \cdot 10^{-3}}{28 \cdot 4.2 \cdot 10^{-4}} = 4.73 \cdot 10^{-6} \ \Omega \qquad (1)$$

Where $D_{kn}$ is average diameter of steel ring, $Q_2$ is number of rotor teeth, $S_{kn}$ is cross area of steel end-ring and $\rho_{Fe150}$ is specific resistivity of solid steel.

The leakage reactance was calculate by well-known equation from [3] and it include magnetic conductivity coefficient of rotor end-rings which are directly attached to rotor stack.

$$\lambda_{ei} = \frac{2{,}3 \cdot D_{kn}}{4 \cdot Q_2 \cdot l_{fe} \cdot \sin^2 \cdot \left( \frac{\pi \cdot p}{Q_2} \right)} \cdot \log \frac{4{,}7 \cdot D_{kn}}{2 \cdot a_{kn} + b_{kn}} = 0.636 \qquad (2)$$

Where $l_{Fe}$ is stator stack, $a_{kn}$ is length of rotor end ring in radial direction and $b_{kn}$ in axial direction. Magnetic conductivity coefficient is then divided by two for one end-ring and leakage inductance of one end-ring between two teeth is calculated, $L_r$=31.98 nH. The conductivity of rotor core was reduce by Russel correction factor, described in []. The final value of rotor conductivity material is $\sigma$ =1.49 MS/m

## 3. FIELD RESULTS

Calculated field distribution for axially slitted rotor at 2% slip are shown in Fig.2 and Fig.3. It can be seen from Fig. 3 that current density and eddy current loss are mainly concentrated on the edge of rotor teeth, under the surface. Fig.4a and 4b shows flux density distribution. The fundamental harmonic has value of 0.6 T.

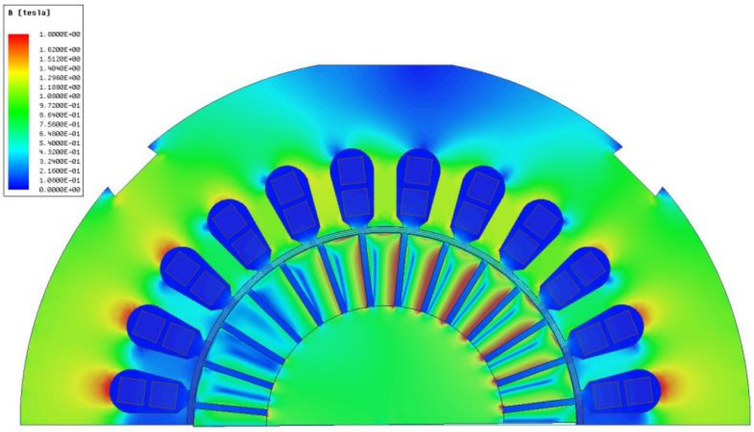
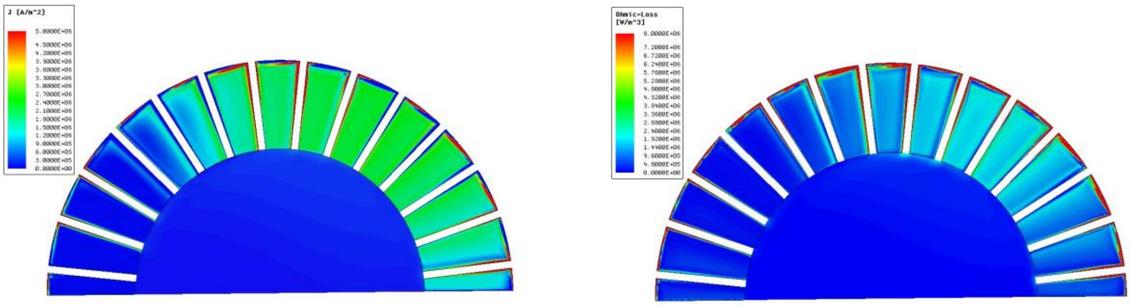
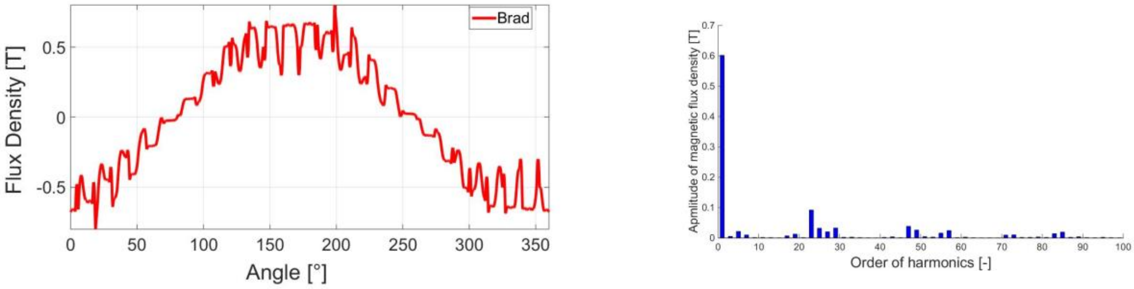


**Figure 2:** Flux density distribution in cross-section area of axially slitted rotor at 2% slip



a) b)

**Figure 3:** Density distribution in cross-section area at 2% slip a) Current density b) Eddy current loss

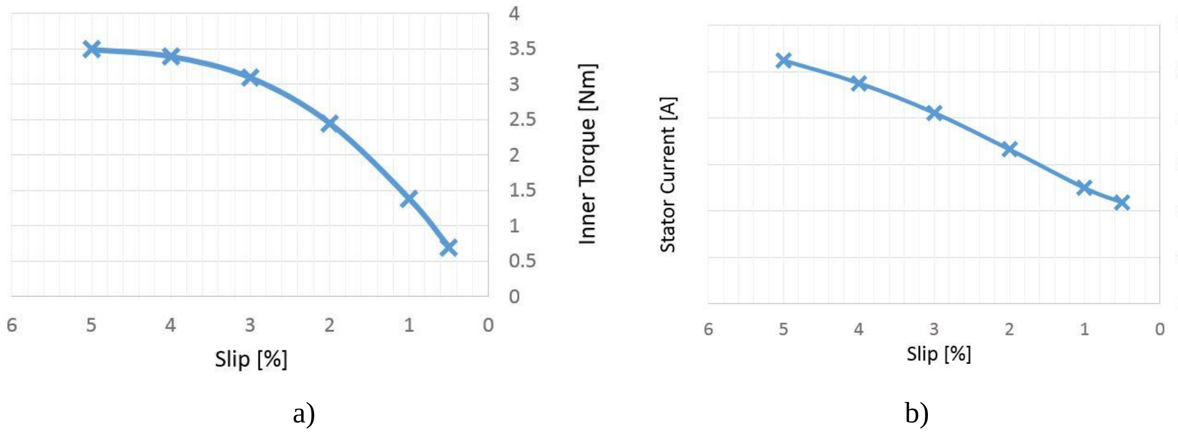


a) b)

**Figure 4:** Air-Gap flux density distribution a) with respect to angular position b) its harmonic spectrum, at 2% slip

## 4. PERFORMANCE CHARACTERISTICS

Performance characteristics, can be seen in Fig.5 and Fig 6, represent motor behavior at different slip. Fig.5a and 5b shows the inner torque and stator input current of motor in dependence on rotor slip. Fig. 6a represent values of stator and rotor losses with respect of rotor slip.



a) b)

**Figure 5:** Motor performance characteristics a) torque vs. slip characteristics b) current vs. slip characteristics

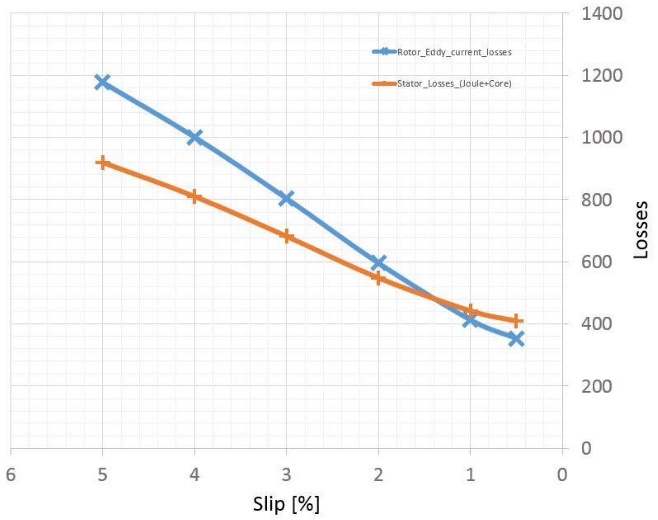


**Figure 6:** Stator and rotor loss vs. slip characteristics

## 5. CONCLUSION

Performance motor characteristic and field distribution has been demonstrated. From field distribution, it can be seen that, eddy current loss are mainly concentrated at rotor surface. Due to, feature modification, the magnetic flux density penetrates deeper than in solid smooth rotor. The analysis by finite element method in ANSYS Maxwell software has shown that axially slitted rotor can be easily examine and therefore it can be start point for other design aspects, for example mechanical and thermal analysis. Our motor is designed to have output power 12kW. Operating point will be located slightly above 2% rotor slip. Mechanical losses caused by friction and ventilation were not included in motor characteristics.

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