# SENSITIVITY ANALYSIS OF AN INDUCTION MACHINE WITH A SOLID ROTOR

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**Abstract**: The main focus of this paper is to show the results of sensitivity analysis of an induction machine with a solid rotor. For the case study, a three-phase induction machine with a squirrel cage is chosen. However, the rotor of this machine is replaced with an axially slitted solid rotor. The electromagnetic model is analyzed by transient simulation using the FEM-based program Ansys maxwell. For the sensitivity analysis, several parameters are changed in a wide range to see the difference in the machine overall performance. Some of the results of these simulations are shown and discussed at the end of this paper.

**Keywords**: Sensitivity analysis, Induction machine, Solid rotor, FEM, Simulation, Transient analysis

## 1 INTRODUCTION

In recent years, the demand for high-speed electrical machines has increased. This is due to the fact that some industrial applications require high rotational speed, as pumps, turbo-compressors, turbo-circulators, and others. For this reason, electrical machines with gearboxes are being replaced with electrical machines with a solid rotor. The main advantages of electrical machines with a solid rotor are withstanding high centrifugal forces, peripheral speed, and temperatures. They are mechanically rigid, highly reliable, compact, and easy to manufacture. Moreover, high-speed electrical machines have better electromagnetic performance and efficiency at higher speeds. This work deals with the methodology of analysis and sensitivity analysis of an induction machine with an axially slitted solid rotor, which is the most widespread solid rotor construction.

## 2 ANALYZED MACHINE

For the case study, an industrially produced three-phase, 4 pole induction machine with single-layer winding and squirrel cage, was chosen. The material of the stator and rotor core is M470-50A. Catalog parameters of the analyzed machine are listed in Table 1.

| Parameter | Unit | Value |
|---|---|---|
| Rated output power | kW | 1.5 |
| Rated torque | Nm | 9.905 |
| Rated input voltage | V | 3x400 (Y) |
| Rated input current | A | 3.43 |
| Frequency | Hz | 50 |
| Rated speed | rpm | 1446.2 |
| Efficiency | % | 84.62 |

**Table 1:** Parameters of analyzed induction machine.

However, the rotor of this machine was replaced with an axially slitted solid rotor. The geometry of the rotor is shown in Figure 1. This rotor is made of a single piece of ferromagnetic material, where the material is stainless steel 1008. With the changed rotor, the overall performance of the machine will be worse, due to the lower rotational speed and the fact that a solid rotor tends to have a large slip and worse performance compared to the rotor with a squirrel cage.

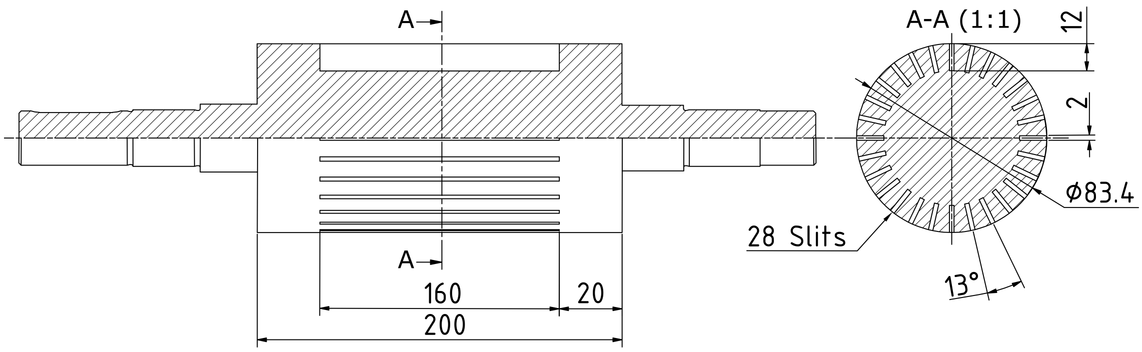


**Figure 1:** Geometry of axially slitted solid rotor.

## 3 THE METHODOLOGY OF ANALYSIS OF ELECTRICAL MACHINES WITH A SOLID ROTOR

Due to the complex physical nature of electrical machines with a solid rotor, analytical methods for the calculation of machine's performance is not the best choice. Most of these analytical methods include some simplification, which impairs the accuracy of the calculated results. This is due to a very complex distribution of relative permeability in the rotor which depends on the material and its B-H curve. Also, the distribution of rotor losses is very complex and depends on the penetration depth of the higher air-gap frequencies. Both of these variables are most pronounced in the axially slitted solid rotor. A much better choice would be 3D FEM-based transient analysis, due to the nature of the rotor construction. However, this type of analysis takes a lot of computation power, memory, and is highly time-consuming. So, the last and best option is 2D FEM-based transient analysis, which takes less computation power, memory and is much less time-consuming. However, the 2D electromagnetic model is not able to take into account the 3D aspects of the rotor construction, such as resistivity and leakage inductance of the rotor end regions. This would result in wrong calculated results, where for example the value of the torque would be too optimistic. In order to take into account the end regions of the rotor, corrective end-effect factors were proposed, as it is stated in [1]. The corrective end-effect factors are adjusting the conductivity of the rotor in the electromagnetic model in a way that includes the resistivity of the end regions of the rotor, with following simple equation:

$$\sigma_{Corr} = \sigma_{Fe} \cdot k, \tag{1}$$

where $\sigma_{Fe}$ is the conductivity of rotor material and $k$ is the corrective end-effect factor. There are two types of corrective end-effect factors that depend on the geometry of the rotor and the slip frequency of the rotor. The chosen formula of corrective end-effect factor based on geometry has according to [2] shape:

$$k_{Russell,M} = 1 - \frac{\tau_p}{\pi l_s} \frac{tanh\left(\frac{\pi l_s}{\tau_p}\right)}{\left(1 + tanh\left(\frac{\pi l_s}{\tau_p}\right) tanh\left(\frac{\pi l_{end}}{\tau_p}\right)\right)}, \tag{2}$$

where $l_s$ is active length of the machine, $\tau_p$ is pole pitch of the rotor and $l_{end}$ is length of the rotor end regions. The chosen formula of corrective end-effect factor based on slip frequency has according to [3] shape:

$$k_{PAN} = 1 - c \cdot \omega_r^{\frac{3}{4}}, \tag{3}$$

where $c$ is an experimental adaptation coefficient (estimated as $c = 0.022$) and $\omega_r$ is angular slip frequency of the rotor. The product of these two corrective end-effect factors gives a total correction factor which is then used in equation (1).

## 4 PROCESS OF SENSITIVITY ANALYSIS

The sensitivity analysis was done by changing individually the value, in a wide range with reasonable limits, of the following 8 parameters: active length of the machine, length of rotor end region, number of stator winding conductors, stator tooth width, stator slot height, length of the air-gap, depth of the axial slits, and width of the axial slits. Each of the new geometry is made with the FreeCAD program, which is an open-source CAD program. The simulations of the sensitivity analysis are done with the 2D FEM program Ansys maxwell. The type of simulation which was used is transient with constant speed, where the constant speed was selected with the respect to the highest efficiency of the machine with the solid rotor. The speed was estimated to be $1322\,rpm$, which means that the slip of the machine increased significantly. The whole process of the simulation was automated using the programing language Python. The algorithm of the sensitivity analysis is shown in Figure 2.

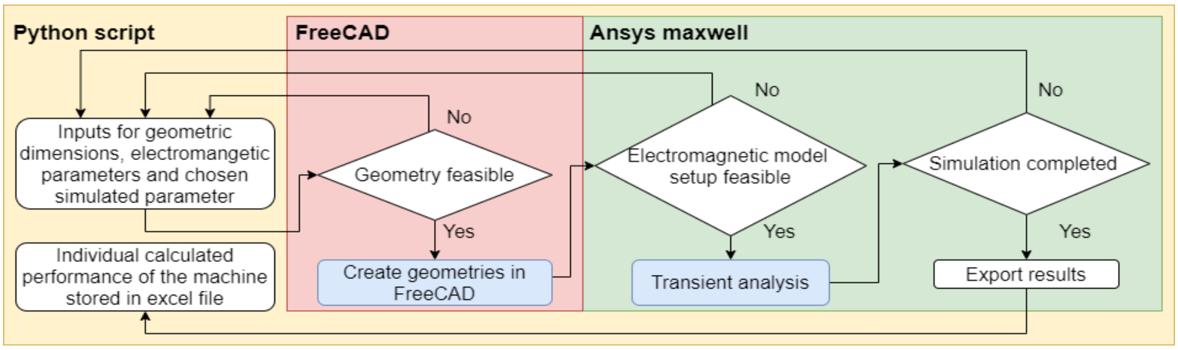


**Figure 2:** Algorithm of sensitivity analysis of an electrical machine with a solid rotor.

## 5 SENSITIVITY ANALYSIS RESULTS

Within the sensitivity analysis, the focus was put mainly on four output parameters of all simulations. These parameters include electromagnetic torque, electromagnetic efficiency, output power, and phase current. All of the results of these four parameters are shown in Figure 3. Here, on the x-axis of the graphs, is the normalized value of a variable, which represents the relative growth of changed parameters. This way, it is possible to put all results together. It is clear from the results, that the overall performance of the machine with the solid rotor is worse, compared to the original one with squirrel cage. This output was expected. It can also be seen that in order to raise effectively torque, output power, and efficiency, it is necessary to increase the active length of the machine. However, this will also increase the size of the machine and phase current, which results in a higher current density of the stator slot. Another improvement could be made by narrowing the axial slits in the rotor. This modification would raise torque, output power and efficiency. It would also decrease phase current and current density of the stator slot. But this modification depends on the manufactures capabilities. By changing slit depth to 150 % it would be possible to achieve higher torque, output power, and efficiency. But this would also increase phase current. After this point, the performance of the machine would be worse. By lowering the number of conductors, the torque and output power would raise. But the efficiency would be lower and phase current would raise. The length of the air-gap is in this machine perfectly design. On the other hand length of the end region does not have much effect on the performance of the machine. And by changing either length or width of the stator slot, the performance of the machine is minimally improved or gets worse.

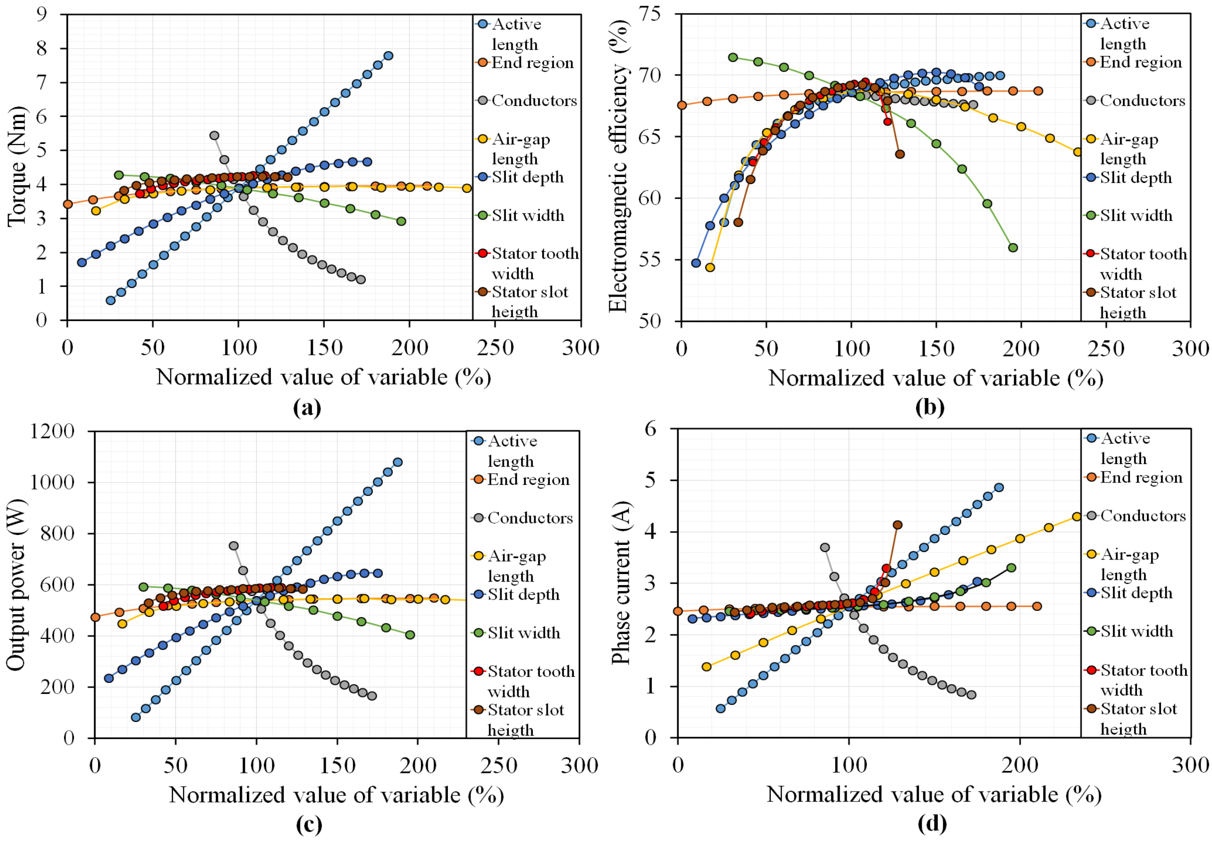


**Figure 3:** Function of: torque (a), electromagnetic efficiency (b), output power (c) and phase current (d) on normalized value of variable.

## 6 CONCLUSION

This paper showed the methodology and process of sensitivity analysis of the induction machine with the axially slitted solid rotor, using the FEM-based program Ansys maxwell. From the results, it can be seen that the machine has worse performance compared to the original machine with squirrel cage. But otherwise, it is a very well-designed machine with some room for improvement. This improvement could be done by adjusting some of the machine parameters described in this paper.

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