A comparison study of the efficiency between an asynchronous radial electrical machine and a synchronous reluctance motor

Georgi Todorov
Laboratory "CAD/CAM/CAE in Industry"
Technical University of Sofia
Sofia, Bulgaria
gdt@tu-sofia.bg

Adrian Ivanov
Department of Electrical Machines
Technical University of Sofia
Sofia, Bulgaria
apiv@tu-sofia.bg

Blagovest Zlatev
Laboratory "CAD/CAM/CAE in Industry"
Technical University of Sofia
Sofia, Bulgaria
bzlatev@3clab.com

***Abstract*— the study concerns a comparison study between an asynchronous radial electrical machine and a synchronous reluctance motor (SynRM). Given that the two machines have no differences in their stator construction and only differ in their rotor constructions it is of interest to see how they compare in different parameters - mainly their efficiency. Additionally, the SynRM rotor construction does not need the casting of a squirrel-cage and no currents are induced into it as it closes the magnetic field with the help of specifically shaped air gaps which create a strong magnetic reluctance in one direction and a weak one in a perpendicular direction.**

***Keywords*— SynRM, synchronous, reluctance, motor, asynchronous, Maxwell, FEM**

I. Introduction

The aim of the study is to create a Synchronous Reluctance Motor (SynRM) given their inherent advantages and to compare it to a conventional Asynchronous Radial Electrical Machines. For these purposes two 2D FEA models are created in order to simulate and compare a 4-pole Radial AC Electrical Machine to a 4-pole Synchronous Reluctance Motor (SynRM) by modifying only the rotor between the two designs.

SynRM motors are also known as synchronous electric motors with a rotor with anisotropic magnetic conductivity. [1]. Some of their main advantages consists of a higher efficiency (up to 95%) [2] thus having a high IE classification (usually IE4 or IE5). This is because the rotor does not consists of a magnetic core and a squirrel cage thus lowering the heat generated in the stator.

ABB Group has emerged as a leader in the field having a wide family of motors from 17 to 350 kW [3] widely produced since 2013.

The ABB Group states that a synchronous reluctance motor in comparison with a conventional induction electrical machine of the same size with a high energy efficiency class IE2 (according to GOST IEC 60034-30-1-2016) has between 10-20% higher efficiency.

II. Input Parameters of an Asynchronous Radial Electrical Machine

For the comparison a 2.2 kW asynchronous radial electrical machine was chosen because of its relatively high market share of electrical machines – Elprom Harmanli AT3 100 LK 4. The laminated stacks of the electrical machine are based on IEC.100/4.90 (SA150T, RA090M) – with outer diameter of the stator of 150 mm and outer diameter of the rotor of 90 mm.

The main characteristics of the motor are shown on table 1.

TABLE I. Characteristics of an Asynchronous Radial Electrical Machine – Elprom Harmanli AT3 100 LK 4

Pole Count	4
Synchronous Speed	1500 min-1
Power	2.2 kW
Nominal Speed @ 50 Hz	1420 min-1
Maximum efficiency at 100% load	86.7%
Power Factor - cosϕ	0.81
Stator Coil Slots	36
Rotor Bar Slots	28

III. Virtual Prototype of an Asyncrhonous Radial Electrical Machine – AT3 100 LK 4

Virtual prototyping by product modelling and simulation is faster in reaching a good result in the prototyping process compared to physical prototyping and can predict dynamic characteristics of the prototype. [4] [5]

1) Geometric Model

A virtual prototype of a Radial Asynchronous Electrical Machine is shown on fig. 1 and was created from the onset as a surface (2D) model in order to simplify the finite element model. The modeled electrical machine is 4-pole machine with a synchronous speed of 1500 rpm. The machine is modeled with a stator (pos. 1) and a rotor (pos. 4) made of electrical steel, stator windings (pos. 2) made of copper, rolled channels in the rotor (pos. 3) with cast aluminum forming the squirrel cage.

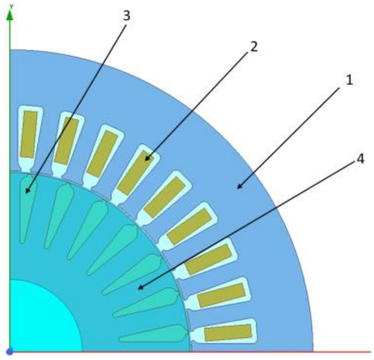

Fig. 1. Virtual prototype of a radial asynchronous electrical machine – AT3 100 LK 4

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2) Boundary Conditions

Given that a two-dimensional model is used, it is necessary to set the depth of the model along the axis of the asynchronous electrical machine. The depth of the simulated motor is 140 mm.

The boundary conditions of the given electrical machine are the definition of the windings for the individual phases of the stator, the end connection of the rotor (necessary because the computational model is two-dimensional and there is no way to short the rotor through its aluminum end rings) and rotor speed. The rotor speed is set at 1420 rpm. The definition of the stator coils and rotor end connection is shown on fig. 2.

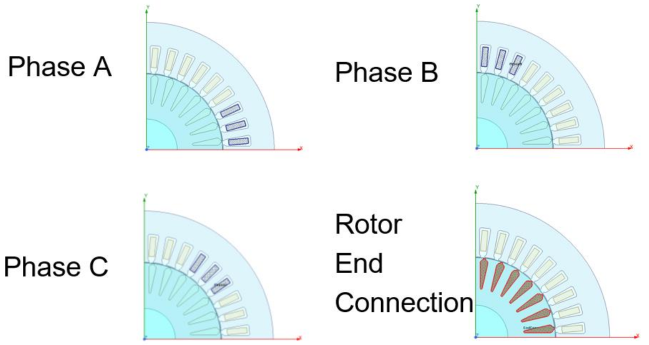

Fig. 2. Defining the phases and rotor end connection of a radial asynchronous electrical machine – AT3 100 LK 4

The electrical circuit which is powering the machine is shown on fig. 2 with a frequency of the input alternating source being 50 Hz.

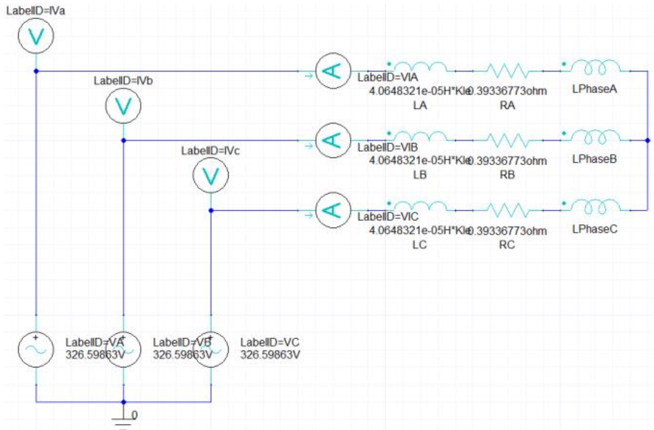

Fig. 3. Electrical circuit for a radial asynchronous electrical machine – AT3 100 LK 4.

3) Results from the virtual prototype of a radial asynchronous electrical machine

The results from the Virtual Prototype are presented in the following aspects – Induced Voltage in the stator, Stator Currents, Torque, Electrical Power and Mechanical Power, as well as the magnetic flux and the current density in the finite element model.

B. Induced Voltage

The induced voltage in the phase windings is up to 200 V with a sinusoidal form as shown in fig. 4.

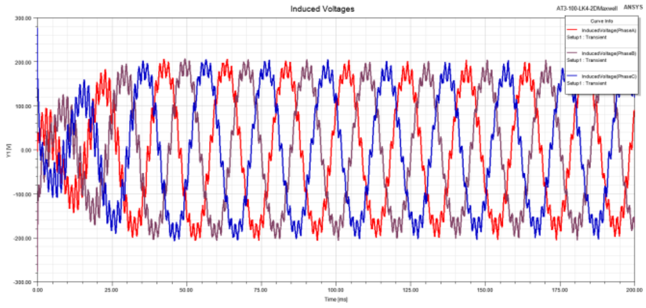

Fig. 4. Induced Voltage in the Stator Windings of a Radial Asynchronous Electrical Machine – AT3 100 LK 4

C. Stator Current

The stator current in the phase windings is up to 12 A after stabilizing with a sinusoidal form as shown in fig. 5.

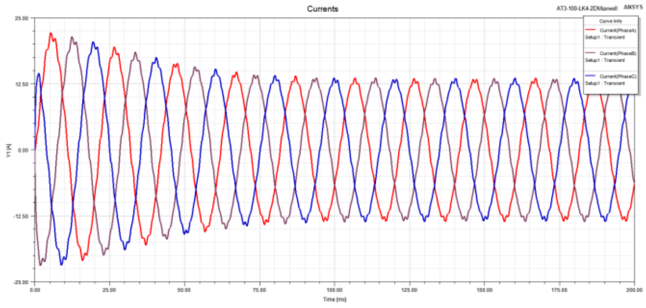

Fig. 5. Current in the Stator Windings of a Radial Asynchronous Electrical Machine – AT3 100 LK 4

D. Generated Torque

The generated torque of the electrical machine after stabilizing of the solution has a maximum of 14.8 Nm and average of 12-13 Nm. This moment is shown on Fig. 6.

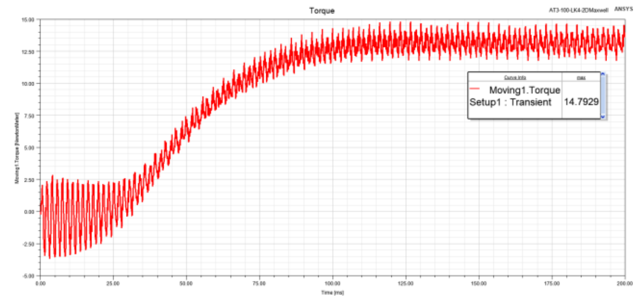

Fig. 6. Generated torque of a Radial Asynchronous Electrical Machine – AT3 100 LK 4

E. Generated Electrical Power

The generated electrical power of the electrical machine after stabilizing of the solution is around 2.1 kW. This power is shown on Fig. 7.

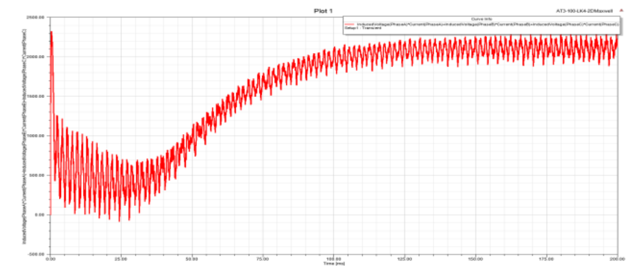

Fig. 7. Generated Electrical Power of a Radial Asynchronous Electrical Machine – AT3 100 LK 4

F. Generated Mechanical Power

The generated mechanical power of the electrical machine after stabilizing of the solution is around 1.96 kW. This power is shown on Fig. 8

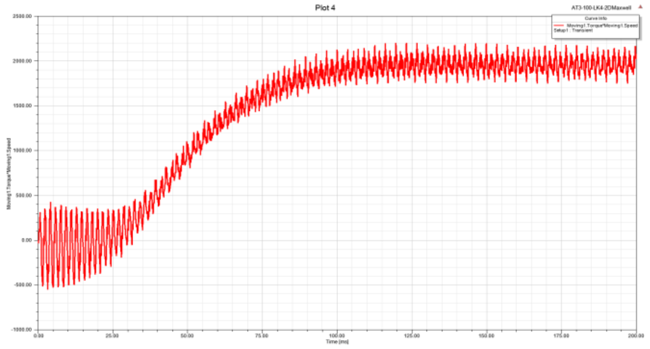

Fig. 8. Generated Mechanical Power of a Radial Asynchronous Electrical Machine – AT3 100 LK 4.

G. Magnetic Flux

The distribution of the magnetic flux is important in order to determine where the magnetic lines close. On fig. 9 distribution of the magnetic flux is shown. The Magnetic flux distribution has an average of 1.6-1.8 T.

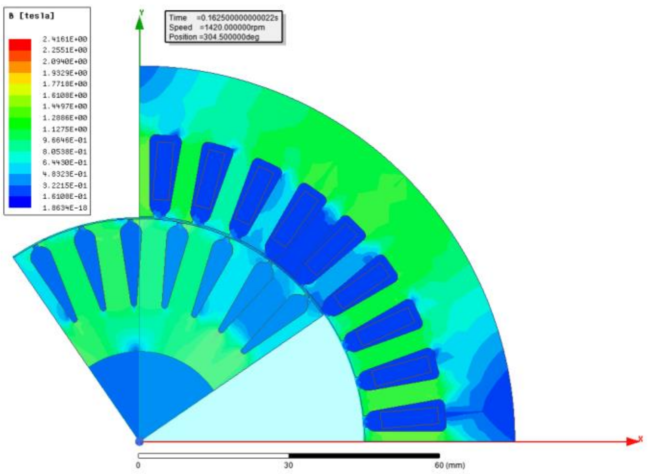

Fig. 9. Magnetic flux of a radial asynchronous electrical machine – AT3 100 LK 4.

H. Current Density in Rotor.

The current density of the induced currents in the rotor is inevitable in a conventional radial asynchronous electrical machine but the induced currents increase the losses of the machine. The current density in the AT3 100 LK 4 induction motor is around 7.5-11.0x10^6 A/m^2. The current density is shown on fig. 10.

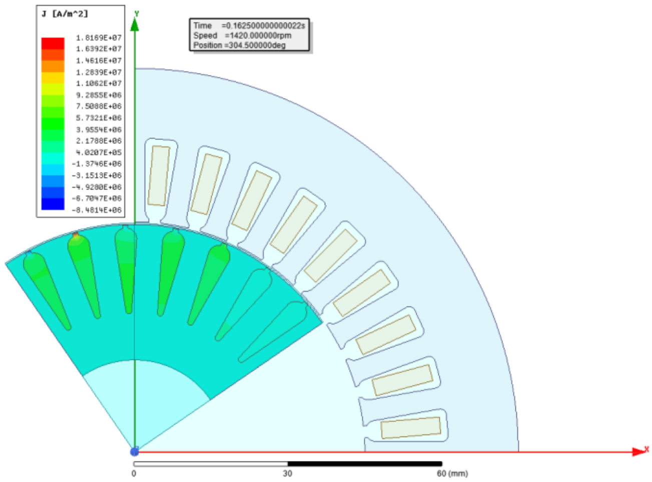

Fig. 10. Current density of a radial asynchronous electrical machine – AT3 100 LK 4

IV. Virtual Prototype of a Syncrhonous Reluctance Motor (SynRM) – SynRM AT3 100 LK 4 modification

1) Geometric Model

A virtual prototype of a Synchronous Reluctance Motor is shown on fig. 11 and is created as a surface (2D) model for simplification of the finite element model. The modeled electrical machine is 4-pole machine with a synchronous speed of 1500 rpm. The machine is modeled with a stator (pos. 1) and a rotor (pos. 3) made of electrical steel, stator windings (pos. 2) made of copper and specifically shaped air gaps (pos. 4) that create an anisotropic magnetic permeability of the rotor. For a 4-pole machine the shown segment needs to be multiplied by 4, for a 6-pole – 6 times, etc.

The only modification done to the motor is the change of the rotor and keeping the stator the same as the one in the radial asynchronous electrical machine AT3 100 LK 4.

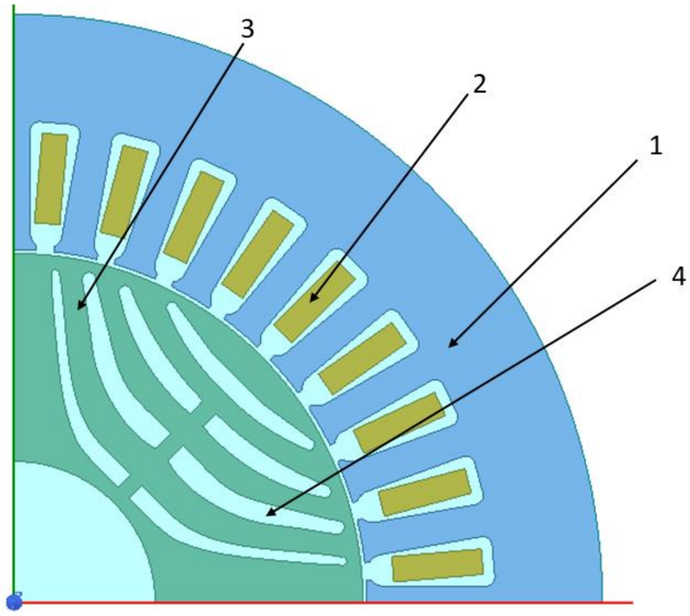

Fig. 11. Virtual prototype of a Synchronous Reluctance Motor – SynRM AT3 100 LK 4

This modification leads to the resultant electrical machine to be considered as a Synchronous Reluctance Machine. [6]

2) Boundary Conditions

Given that a two-dimensional model is used, it is necessary to set the depth of the model along the axis of the asynchronous electrical machine. The depth of the simulated motor is 140 mm.

The boundary conditions of the given electrical machine are the definition of the windings for the individual phases of the stator, angular orientation at the initial moment and rotor speed. The angular orientation of the rotor is offset by 27.5o from the position shown on fig. 11. Additionally, the rotor speed is set at 1500 because the motor is expected to be synchronous. No end connection boundary condition is needed given that the magnetic permeability of the motor is anisotropic and no squirrel cage is needed thus no currents are expected to be induced in the rotor. The definition of the stator coils is shown on fig. 12.

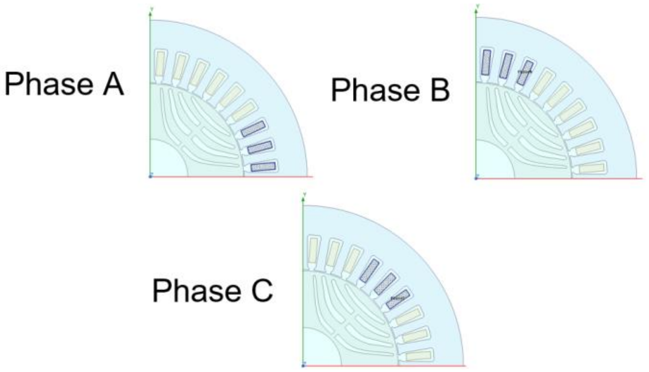

Fig. 12. Defining the phases of a Synchronous Reluctance Motor – SynRM AT3 100 LK 4

The electrical circuit which is powering the machine is shown on fig. 13 with a frequency of the input alternating source being 50 Hz.

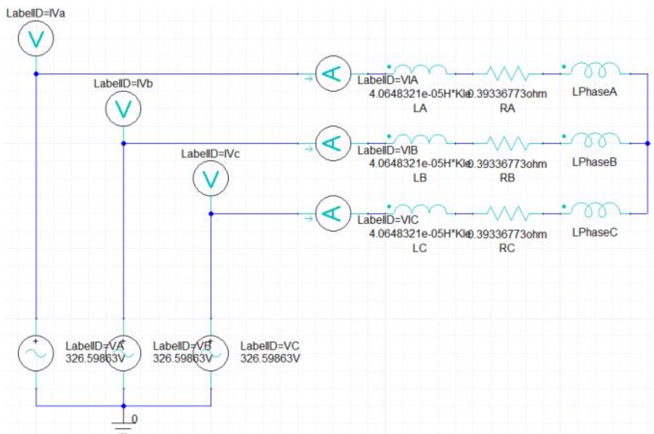

Fig. 13. Electrical circuit for a Synchronous Reluctance Motor – SynRM AT3 100 LK 4

3) Results from the virtual prototype of a Synchronous Reluctance Motor – SynRM

The results from the Virtual Prototype are presented in the following aspects – Induced Voltage in the stator, Stator Currents, Torque, Electrical Power and Mechanical Power, as well as the magnetic flux and the current density in the finite element model.

B. Induced Voltage

The induced voltage in the phase windings is up to 175 V with a sinusoidal form as shown in fig. 14.

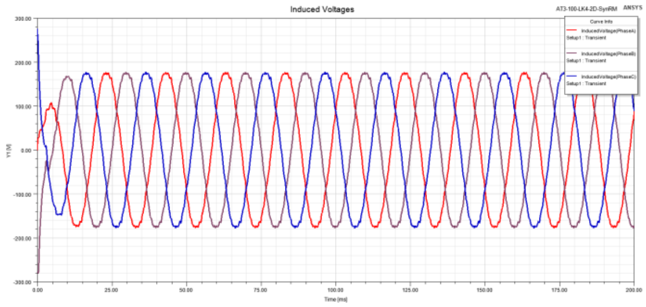

Fig. 14. Induced Voltage in the Stator Windings of a Synchronous Reluctance Motor – SynRM AT3 100 LK 4

C. Stator Current

The stator current in the phase windings is up to 14.2A after stabilizing with a sinusoidal form as shown in fig. 15.

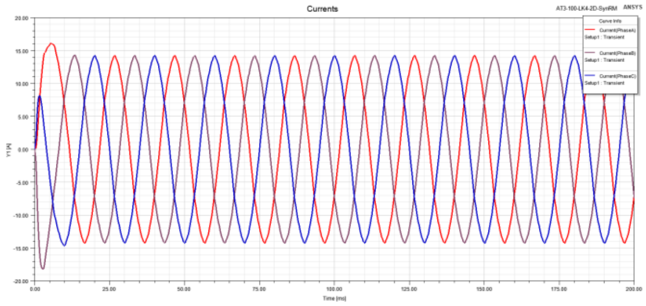

Fig. 15. Current in the Stator Windings of a Synchronous Reluctance Motor – SynRM AT3 100 LK 4

D. Generated Torque

The generated torque of the electrical machine after stabilizing of the solution has a maximum of 14 Nm and average of 11.5-13 Nm. This moment is shown on Fig. 16.

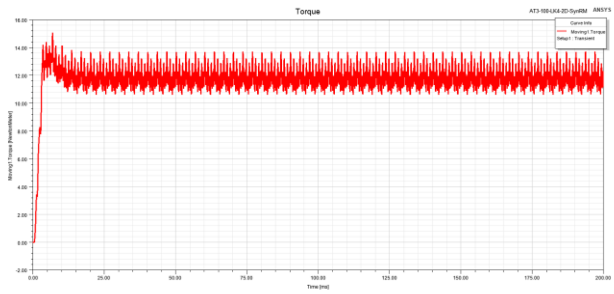

Fig. 16. Generated torque of a Synchronous Reluctance Motor – SynRM AT3 100 LK 4

E. Generated Electrical Power

The generated electrical power of the electrical machine after stabilizing of the solution is around 1.9 kW. This power is shown on Fig. 17.

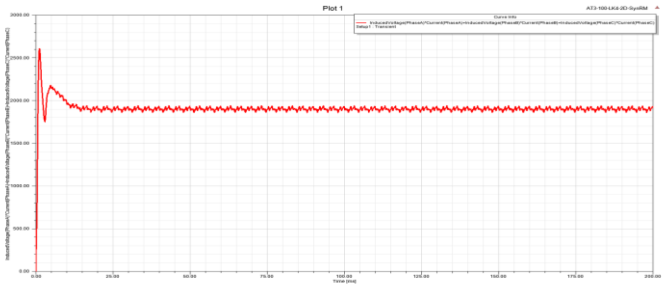

Fig. 17. Generated Electrical Power of a Synchronous Reluctance Motor – SynRM AT3 100 LK 4

F. Generated Mechanical Power

The generated mechanical power of the electrical machine after stabilizing of the solution is around 1.86 kW. This power is shown on Fig. 18

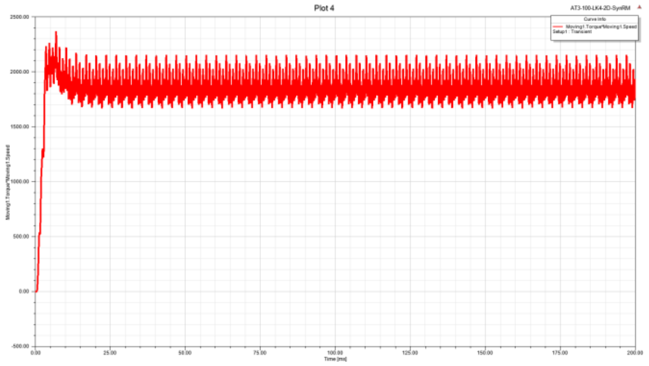

Fig. 18. Generated Mechanical Power of a Synchronous Reluctance Motor – SynRM AT3 100 LK 4

G. Magnetic Flux

On fig. 15 and fig. 16 the distribution of the magnetic flux is shown both in the stator and the rotor. The Magnetic flux distribution has an average of 1.2-1.6 T with peak values of 2.0 T.

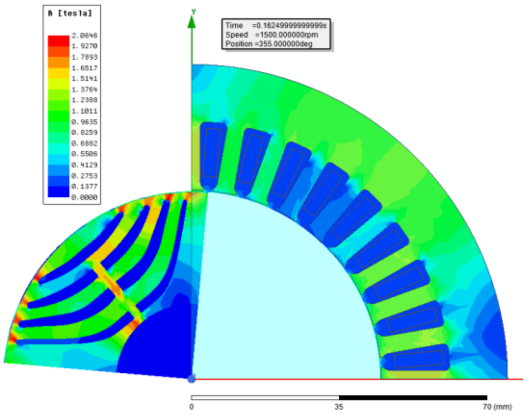

Fig. 19. Magnetic flux of a Synchronous Reluctance Motor – SynRM AT3 100 LK 4

H. Current Density in Rotor.

No currents are induced the rotor because no cage is present and the motor works in a synchronous state. This is shown on fig. 20 where it is clearly seen that the rotor has a current density of 0 A/m^2.

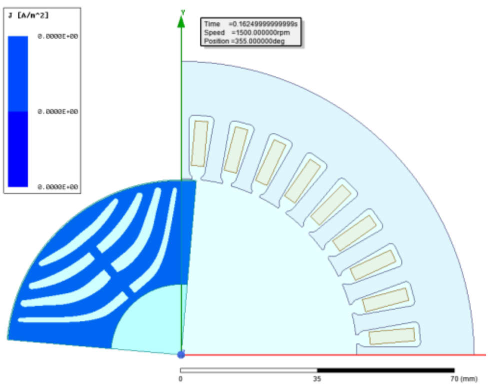

Fig. 20. Current density of a Synchronous Reluctance Motor – SynRM AT3 100 LK 4

V. Conclusion

Based on the research, the following conclusions were made for AC motor AT3 100 LK 4:

- The modeled AC machine has an electrical power of 2.1 kW and mechanical power of 1.96 kW.
- The modeled AC machine has a calculated efficiency of 93.12%
- The difference between the modeled and real efficiency is 6.9% which is acceptable given no aerodynamic and mechanical losses are accounted.
- The induced current in the squirrel cage of the rotor is expected and creates additional losses.

Based on the research, the following conclusions were made for ***SynRM AT3 100 LK 4***:

- The modeled SynRM machine has an electrical power of 1.9 kW and mechanical power of 1.86 kW.
- The modeled SynRM machine has a calculated efficiency of 98.11%
- The speed of the rotor is 1500 rpm.
- No current is induced in the rotor.

Based on the research, the following comparisons and conclusions can be made:

- The modeled SynRM machine has a 5.01% higher calculated efficiency than the calculated efficiency of the AC radial machine.
- Given that no current is induced into the SynRM rotor no losses can be generated from it.
- The position of the rotor relative to the rotating magnetic field is important in order to be in a low reluctance state. Thus starting this motor should be done slowly with a variable frequency drive or having position sensors for low and high reluctance state and a simple drive system that takes the position into account.
- Based on the research a physical prototype of a Synchronous Reluctance Motor (SynRM) is being manufacture in order to validate the higher efficiency of the design compared to the AC radial electrical machine.
- Additionally, the manufacture prototype will be used to evaluate the real efficiency of the SynRM which is expected to be 5%-6% lower than the calculated efficiency of 98.11%.

Acknowledgment

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