COMPARISON OF COPPER LOSSES OF LITZ WIRE AND PARALLEL WIRES IN HIGH SPEED INDUCTION MOTOR

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Abstract: The paper deals with design of stator winding in 3 kW 180 000 rpm high-speed induction motor. It shows influence of skin and proximity effects on losses in the winding. Examined types of winding are a solid wire, a wire with parallel strands and a Litz wire.

Keywords: high-speed machine, induction motor, skin effect, proximity effect, winding

1 INTRODUCTION

In the last years high-speed machines have become increasingly more popular and a lot of research have been done to study them. They have high power density and reduce the complexity of drive by removing the need for gears [1]. Dimensions of the drive can be smaller in comparison with conventional drives. The applications of high-speed drives are for example compressors, spindles, milling machines and flywheels [2].

When designing a high-speed machine, the compromise between mechanical durability and electromagnetic efficiency needs to be made. Centrifugal forces cause a high amount of mechanical stress in the rotor. When looking at induction motors, the rotor it is often made of a solid piece of high tensile steel to enhance the durability [3]. The most robust rotor topology is a smooth solid rotor. It's torque generation capability can by enhanced by axially slitting the rotor. This solution is simple to produce and cheap. It also solves the issue with a different thermal expansion of used materials that cause an additional mechanical stress in squirrel cage rotors [4].

The high frequency of a power supply of the machine cause the skin and proximity effects in a stator winding to be a major factor which need to be addressed. These effects are scaled by dimensions of the wire in the winding. To reduce them, the wires need to be significantly smaller than the depth of penetration. This can be achieved by dividing the wires into parallel strands. These parallel strands need to be twisted to eliminate the circular currents which cause additional losses [3].

The best high frequency wire for winding is a Litz wire. It consists of parallel branches of strands which are twisted and every strand goes through every position of whole Litz wire. Ideal Litz wire has an AC resistance equal to a DC resistance [5].

2 STUDIED MACHINE

The studied machine was 3 kW 180 000 rpm induction motor with a solid axially slitted rotor. The number of stator slots was chosen according to the basic principles in [3]. The winding is a double layer fractional slot winding to reduce higher harmonics of flux density in the air gap. The rotor steel was chosen to be 41CrMo4. The high frequency of stator winding demands usage of a low iron loss steel NO10. Basic parameters and dimensions of the machine are in table 1.

Rated rpm	180 000	min^{-1}
Rated Output Power	3	kW
Number of Poles	2	
Rated Amplitude of Phase Voltage	300	V
Stator Winding Connection	Star	
Number of Turns in Series of the Stator Winding	36	
Rated Stator Frequency	3125	Hz
Number of Stator Slots	12	
Number of Rotor Slits	16	
Stator Outer Diameter	100	mm
Rotor Outer Diameter	30	mm
Air Gap Length	1.5	mm
Active Length of Motor	30	mm

Table 1: Parameters of designed induction motor

To find the most advantageous winding design for motor FEM software was used. The simulation was made by 2D transient analysis with step of 1/800 of period to properly simulate the skin and proximity effects in the winding. The rotor end resistance was taken into account by reducing the conductivity of rotor material according to [6].

According to [7], only one modelled stranded coil is enough to determine the skin and proximity loss increase in the winding. The rest of coils are modelled as rectangles with area equal to total copper area of the wires in the layer. In those coils the eddy effects are neglected, the mesh can be coarser and the simulation can be therefore faster.

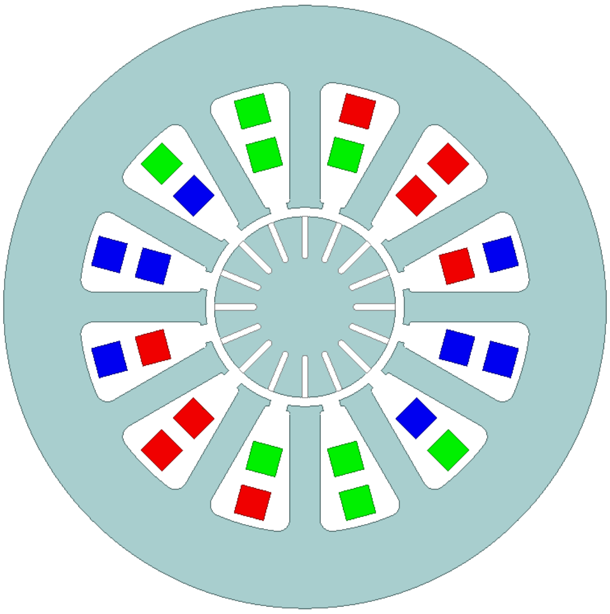


Figure 1: Cross-section of studied motor

Simulated winding combinations are the solid wire, 2 and 3 parallel strands wire and the Litz wire. Slot dimensions were the same for all wire types, only the wires were changed in the simulations. The Litz wire has a small copper fill factor and the stator slots had to be relatively big. This meant non-Litz wires were placed in the back of the slot where the changes of flux density which reduce the proximity effect.

The parallel strands were connected in an external circuit. The end winding resistance and inductance of a phase were computed analytically according to [3]. The equation (1) shows a calculation of phase end winding inductance L_w.

$$L_\mathrm{w} = \frac{2}{p} N^2 \mu_0 l_\mathrm{w} \lambda_w \tag{1}$$

where p is the number of pole pairs, N is the number of turns of a winding in series, μ_0 is the permeability of vacuum, l_w is an average length of the end winding and λ_w is a permeance factor.

The total end winding inductance for the stranded part of circuit is the fourth of L_w as only one of four coils was modelled. This inductance is then multiplied by number of strands to calculate the inductance for each strand. The same applies to the resistance of the strand. The end winding resistance was assumed to be without the skin and proximity effects as magnetic fields are difficult to assess in the end winding area.

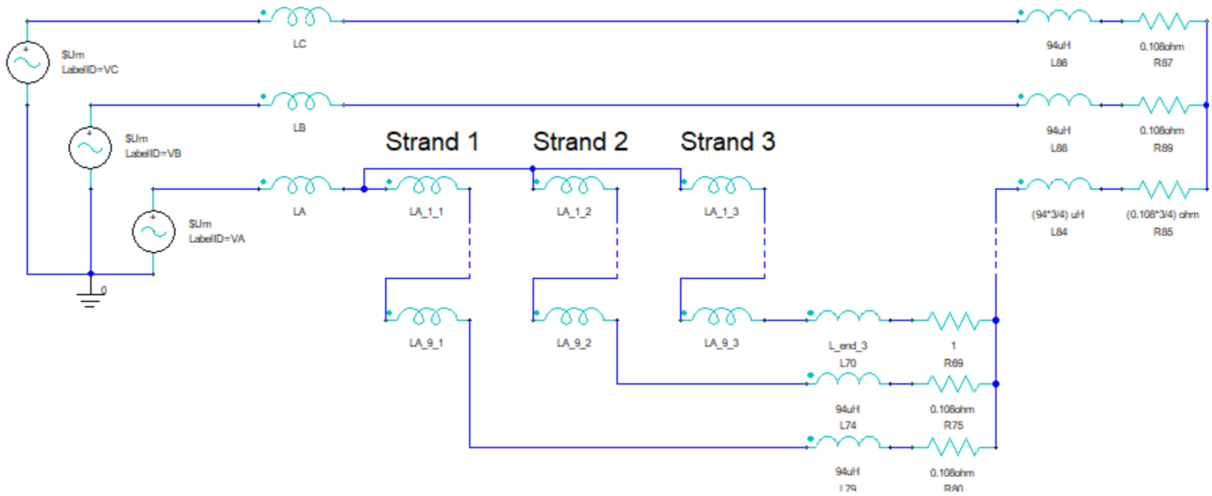
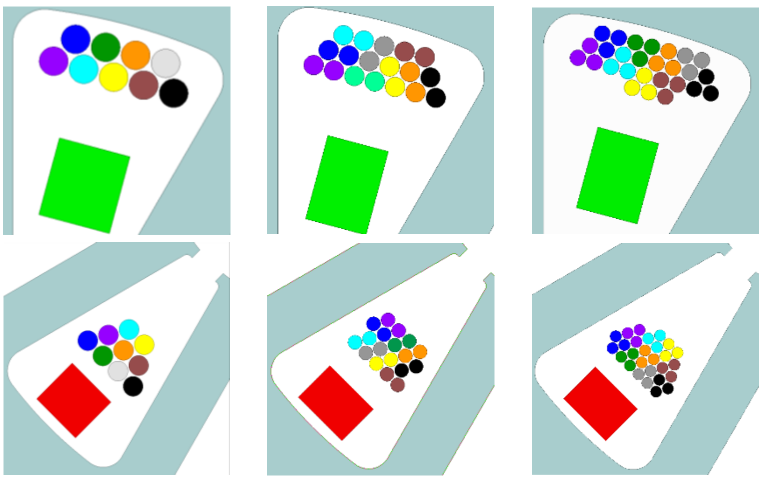


Figure 2: External circuit used in simulations for simulation of the 3x1mm wire



A) B) C)

Figure 3: Stranded coil used in simulation, conductors of the same turn have same color A) 1.8mm solid wire B) 2x1.25mm wire C) 3x1mm wire

3 SIMULATION RESULTS

The resistance factor can be used to compare how suitable the wire is for a high frequency operation. It is the ratio between AC and DC losses. DC losses were computed by simulating without eddy effects in the winding.

Wire type		1x1.8mm	2x1.25mm	3x1mm	105x0.18mm Litz
Total copper area	(mm^2)	22.90	22.09	21.21	24.00
Resistance factor	(-)	3.45	1.46	1.20	1
Total copper losses	(W)	133.8	106.8	106.5	91.3

Table 2: Results of simulation for different wires

As figure 4 shows, the current density is higher in the bottom layer of the winding where the leakage flux is higher. The wires closer to the slot opening are also more affected. The highest current density in the solid 1.8mm wire reaches 3.2 times of the nominal value.

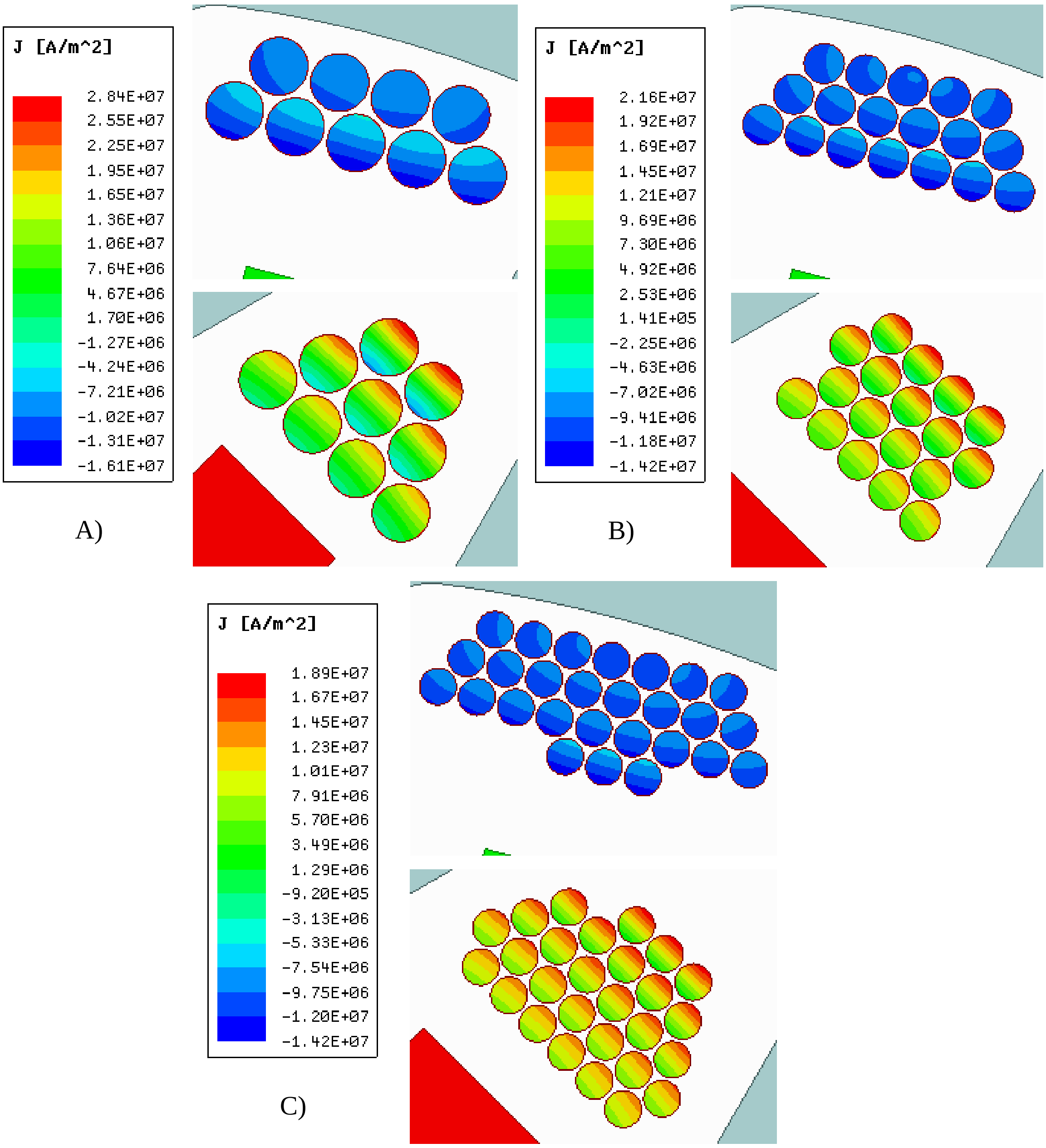


Figure 4: Current density A) 1.8mm solid wire B) 2x1.25mm wire C) 3x1mm wire

4 CONCLUSION

The results of simulations prove that the proximity effect can cause a substantial increase in copper losses of a high speed machine. The placement of conductors in the slot have a big impact on losses in the active part of machine. Conductors in the back of the slot produce lower amount of losses.

By neglecting the eddy effects in the end winding, total copper losses in the motor are not so different even between the solid 1.8mm wire and the Litz wire. Copper losses in the solid 1.8mm wire are 3.45 times higher than in the Litz wire. Dividing the wire into parallel strands helps to reduce the losses to 1.46 times of the Litz for 2 strands and 1.20 times of the Litz for 3 strands.

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