COPPER LOSSES IN PARALLEL WIRES AND LITZ WIRE IN PERMANENT MAGNET SYNCHRONNOUS MACHINE

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Abstract: The paper is focused on comparing the effects of a winding made of the solid wire and the Litz wire to the copper losses in a 3kW 180 000 RPM high-speed permanent magnet synchronous motor. It shows the influence of skin and proximity effects on a current density and copper losses in the wires. The paper uses data from results of FEM simulations.

Keywords: High-speed machine, synchronous machine, proximity effect, winding

1 INTRODUCTION

The high-speed permanent magnet synchronous machines have an advantage of a high power density. It is achieved by a high operating frequency of the machine. With that comes an increased demand on the stator steel and the stator winding. The eddy effects are one of the main reasons for the increased losses in both of those cases. To mitigate those effects, the best available solution is the usage of thinner and superior quality steels and the Litz wire. [1]

The Litz wire is a special type of wire consisting of many parallel strands of a small diameter. The strands are twisted so that every strand comes through every position in the whole Litz to decrease the induced voltage between the strands. The strands can be organized into branches to allow better manufacturability and flexibility. The strands in the branch are twisted and the branch is then twisted with other branches. One of the disadvantages of the Litz wire is a higher prize and a lower fill-factor. An ideal Litz wire has the same AC and DC resistance. [2]

It is generally advised to use a winding with wires of smaller diameter than the depth of penetration to reduce the skin effect [3]. The proximity effect is caused mainly by a leakage flux in the stator slot and needs to be carefully addressed by the placement of parallel wires when using them. When placed incorrectly, the induced circulating currents will cause additional losses. It is therefore advised to place the parallel strands into approximately the same radial position in the slot [4].

A similar subject as this paper was studied in [5]. The studied machine in that case was an induction motor of the same nominal speed and power as the synchronous machine in this paper. The results showed the increase of copper losses for the solid wire in the active part of a machine up to 3.5 the copper losses for a Litz wire.

2 STUDIED MACHINE

The machine in which the skin and proximity effects were studied was a 3 kW 180 000 RPM permanent magnet synchronous motor. The motor is planned to be used in a compressor application. The stator core is made of NO10 steel. The permanent magnet in the rotor is mechanically supported by a carbon fibre sleeve. The winding is a double-layer tooth coil winding to reduce the length of the end winding. The basic parameters of the motor are in Table 1.

Rated RPM	(min^{-1})	180 000
Rated Output Power	(kW)	3
Number of Poles	(-)	2
Rated Amplitude of Phase Voltage	(V)	300
Stator Winding Connection	(-)	Star
Number of Turns in Series of the Stator Winding	(-)	80
Rated Stator Frequency	(Hz)	3000
Number of Stator Slots	(-)	6
Stator Outer Diameter	(mm)	125
Rotor Outer Diameter	(mm)	22
Air Gap Length	(mm)	3
Active Length of Motor	(mm)	25

Table 1: Parameters of the studied synchronous motor

To properly analyse the eddy current effects in different types of the winding, a FEM software was used. In the first step, the machine model was created with a winding made of the Litz wire. The feasibility of the model was verified by a 2D transient analysis. In the next step, the winding of one phase was modelled using individual stranded wires. The transient analysis was done with a step of 1/800 of the period. According to [6], the simulation step for high-speed machines is to be at least 1/400 of the period, which was satisfied.

According to [3], it is sufficient to model only one phase of the machine to be able to find out the accurate copper losses. The rest of the phases are modelled as the areas of the same cross section as the sum of the wires in the according half slot. The eddy effects are not calculated in these phases and the copper losses are obtained only from the stranded winding. The simulation time is therefore reduced. The next thing which reduces simulation time is a usage of symmetry of the machine. The windings were supplied by an ideal three-phase current source with an effective current 7.4 A to achieve its nominal power.

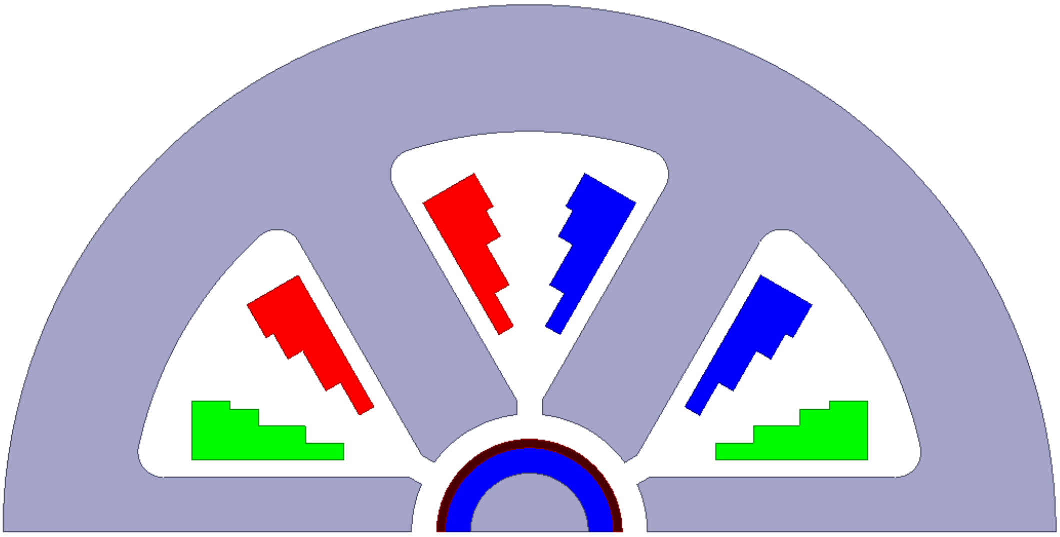

Figure 1: Cross-section of the studied motor

The studied winding wire combinations are the solid wire, 2 and 3 parallel strands wire and the Litz wire. There are no other changes in the machine between the simulations to show only the effect of the winding on the copper losses. The external circuit was used to properly connect individual strands of the stranded winding. Each strand included its end winding resistance and inductance which were computed analytically according to [6]. The resistance of the end winding area was assumed to be without the skin and proximity effects as it is difficult to assess their influence in this area. The calculation of the inductance is based on the calculation of the inductance of an air-cored solenoid and it is shown in equation (1).

$$L_{\mathrm{end}} = \frac{Q_s}{m}\mu_0\mu_{\mathrm{env}}\frac{\left(\frac{z_q}{2}\right)^2 \pi (l_{\mathrm{ew}})^2}{h} \qquad (1)$$

where Q_s is the number of stator slots, m is the number of phases, μ_0 is the permeability of vacuum, μ_{env} is the relative permeability of environment in the end winding area ($\mu_{\mathrm{env}} = 2$ was used in the calculation), z_q is the number of wires in the slot, l_{ew} is the radius of end winding and h is the height of the end winding.

An example of the external circuit used in simulation of winding with 3 parallel strands is shown in Figure 2. In this case the resistance and inductance for individual strands are 3 times the values for whole phase as they are connected parallel and their combination must make the total value for the phase.

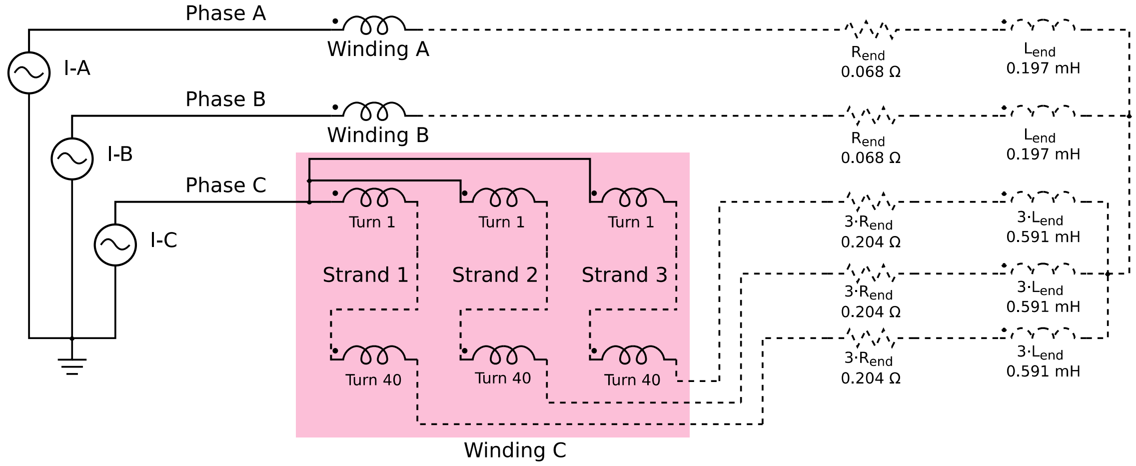

Figure 2: External circuit used in simulations of the 3x0.95mm wire

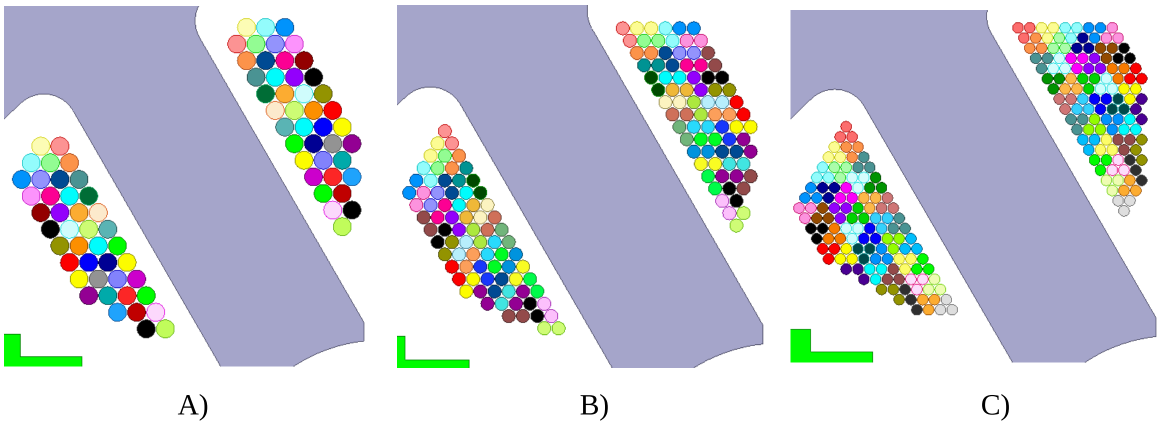

Figure 3: Stranded winding of the model, conductors of the same turn have the same colour A) 1.6mm solid wire B) 2x1.12mm wire C) 3x0.95mm wire

3 SIMULATION RESULTS

Table 2 shows the copper losses for each type of the wire. The losses in the table are the total losses for all three phases. The computed copper loss in the stranded winding was simply multiplied by the number of phases. The resistance factor is used to easily compare the influence of skin and proximity effects. It is a ratio of losses with skin and proximity effects and losses without those effects.

Wire type		1x1.6mm	2x1.12mm	3x0.95mm	435x0.08mm Litz
Total copper area in half of the slot	(mm^2)	80.38	78.78	85.02	83.24
Resistance factor	(-)	3.11	1.86	1.73	1.00
Copper losses in active part of motor	(W)	23.0	14.0	12.1	7.1
Total copper losses	(W)	34.6	25.8	23.1	18.3

Table 2: Results of the simulations for different wires

Figure 4 shows the current density in the winding. The skin and proximity effects cause the peak current density in some strands to locally reach values up to 24 A/mm^2 for 1.6 mm solid wire and 16.3 A/mm^2 for 3x0.95 mm wires. These values are 4.64 and 3.33 times higher than the nominal peak current density.

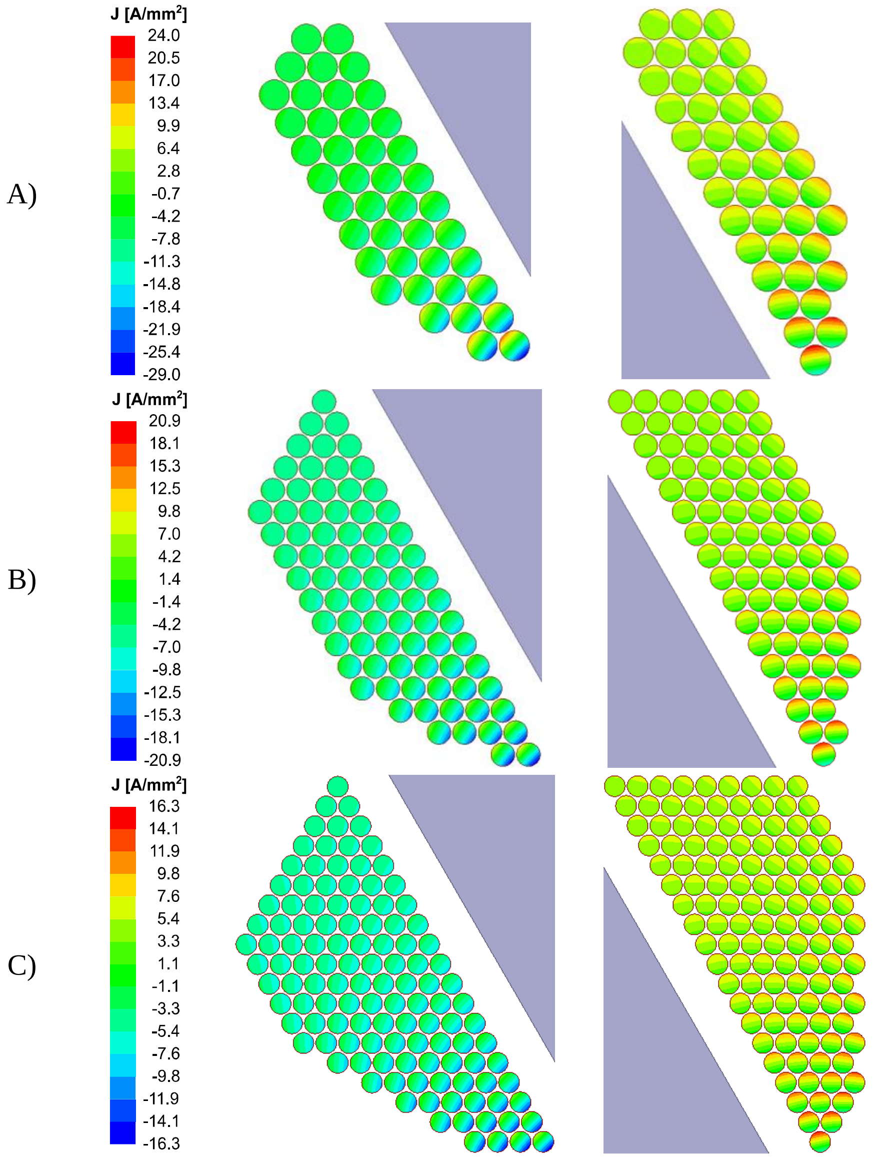

Figure 4: Current density A) 1.6mm solid wire B) 2x1.12mm wire C) 3x0.95mm wire

4 CONCLUSION

The results of the simulations show a substantial increase of copper losses in the synchronous machine when using a solid wire and wires consisting of 2 and 3 parallel strands instead of a Litz wire. One of the main reasons for the increase is believed to be the proximity effect, because the highest current density in the winding is located toward the opening of the slot and toward the other half of the slot.

The resistance factor for the solid 1.6mm wire is 3.11 times the Litz wire. For the parallel 3x0.95mm the factor reaches 1.73. It is assumed that with a bigger number of smaller parallel strands the resistance factor would be even lower but the placement of the strands would need to be carefully assessed as the induced circular currents could cause an increase in the losses.

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