Title:

Helical Retaining Sleeve for Eddy Current Loss Reduction in High-Speed SPM Machine

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Abstract

A rotor retaining sleeve is mechanically necessary in the structure of high-speed SPM machines to prevent structural failure. However, the significant eddy current loss within metal sleeves leads to a reduction in electro-magnetic efficiency and serious thermal and mechanical issues. Therefore, several techniques and methods have been proposed and developed to reduce such losses. In this paper, a helical retaining sleeve is proposed to reduce losses by cutting the flow path of the eddy currents. Using FEA, a comparison is made of the electromagnetic and mechanical performance of the proposed sleeve against a conventional sleeve having the same material and dimensions. It is concluded that the eddy-current loss reduces significantly when the helical sleeve is used, whereas the mechanical stress is broadly unchanged in the central region of the rotor with only a small increase around the ends when compared with the conventional sleeve.

Keywords

Eddy-current, high-speed machine, loss reduction, mechanical stress, PM Machine, SPM Machine, retaining sleeve.

1.1. Introduction

High-speed permanent magnet (PM) machines have attracted the attention of industry over their counterparts of induction and switched reluctance due to their advantages of high power density and efficiency [1]. However, eddy current loss in the conductive parts of the rotor, i.e. magnets and sleeve, due to unsynchronized time and space harmonics is considered a serious issue. In addition to the reduction of the overall efficiency, rotor loss leads to a temperature increase that could cause mechanical degradation of the rotor and reduce the magnetic productivity of the magnets.

Several methods have been proposed to reduce the rotor eddy current by reducing the current time harmonics. Since the inductance of high-speed PM machines is usually small, current ripples due to pulse width modulation (PWM) switching are, therefore, large. To combat this, external inductances are used, leading to increased system size and cost [2]. As an alternative, pulse amplitude modulation (PAM) has been proposed to reduce the current ripple. This consists of a DC-DC converter feeding a six-step inverter. Although current harmonics still exist, the waveform shape will essentially be sinusoidal [3]. In addition to increasing the complexity of the drive, this method may lead to higher rotor loss since the waveform shape highly depends on the drive structure [4]. Another concept, the inter-leaved inverter, has been proposed to solve several issues with high-speed drives including current harmonics [5]. Inter-leaving consists of using two inverters feeding two set of windings with two current waveforms, one of which has a shifted triangular carrier. This results in a shift in the current ripples and therefore reduces the current harmonics in the machine [6]. However, using two inverters leads to more drive complexity.

Space harmonics have also been targeted for reduction in order to reduce rotor eddy current generation. A closed-slot stator topology has been proposed to reduce the space harmonics and consequently the rotor loss [7]. However, this topology leads to winding difficulties, and therefore segmentation efforts need to be considered [8]. Similarly, a slot-less topology has been proposed, however, high copper losses are considered a disadvantage here [9]. Additionally, a large airgap has been proposed to reduce the space harmonics but this comes at the expense of torque output [10].

As an alternative to targeting the factors stimulating eddy current generation, several techniques applied to the rotor have proposed to reduce the loss. Axial segmentation of either or both of the magnets and sleeve, as well as radial segmentation of the magnets, are reported in [11-12]. A copper layer or double sleeves are used to shield the harmonics in [13-14]. Although these methods are effective in reducing the rotor loss, the extra cost, processing and assembly complexity make them unattractive. Finally, sleeve shaping including axial and radial grooving [15] and axial gaps [16] are proposed to reduce the eddy current flow. However, extra machining of each individual sleeve as well as the degradation of the mechanical strength of the sleeve, make these approaches unfavorable for the industry.

In this paper, a new approach to reducing the rotor loss is proposed by using a helical sleeve. Such a sleeve will have the same effect with regard to cutting the eddy current path as axially segmenting the sleeve, , and is easier to manufacture and assemble . Electromagnetic analysis of the rotor loss and mechanical stress analysis of the sleeve is reported and compared with a conventional solid sleeve. The influence of helical turn pitch on the rotor loss and mechanical stress is studied. Finally, rotor dynamics, durability, manufacturing and assembly considerations are discussed.

1.2. Helical Sleeve

Fig. 1 presents the helical sleeve. It consists of a torsion spring-like shape, the spring has a quadrilateral cross-section, and it is coated with insulation material.

Spring manufacturing is a widely established industry. Torsion springs made of Inconel, having a square or rectangular cross-section and coated with an electrically insulating material are widely manufactured around the world.

The quadrilateral cross-section leads to a smooth sleeve surface with possibly small grooves/gaps between the helix turns. Therefore, the impact on rotor dynamics and windage loss are not expected to be significant.

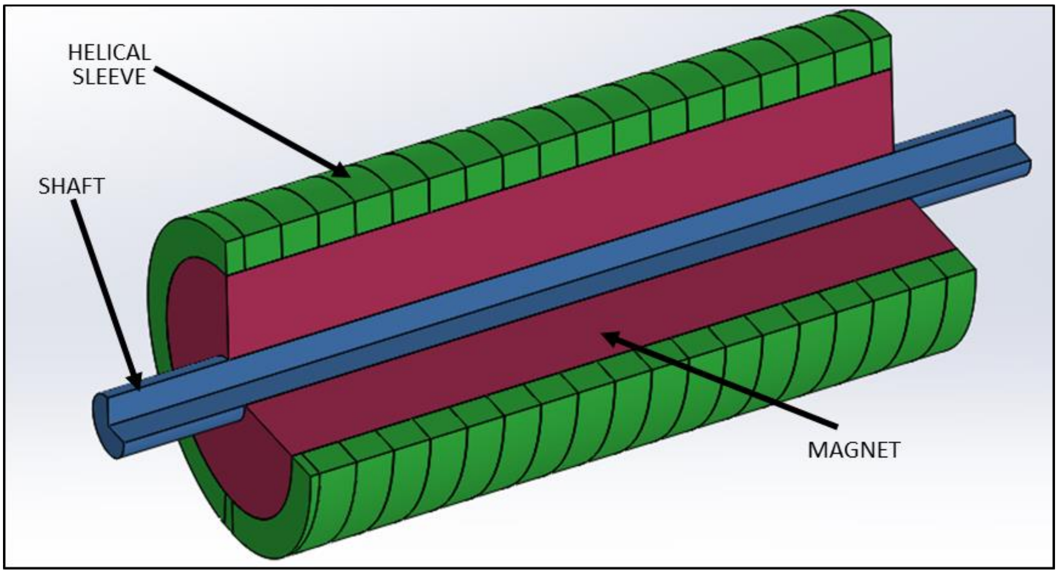


Fig. 1. Rotor assembly with helical retaining sleeve.

1.3. Electrical Machine

The electrical machine used in this study is a surface-mounted permanent magnet (SPM) with 18 slots in the stator and 1 pole pair of parallel magnetized magnets. Fig. 2 presents a cross-section of the machine and Table 1 lists the design parameters of the machine. This machine is designed for electrically-assisted turbocharger (EAT) application. In this application, an electrical machine is placed between the turbine and the compressor of the turbocharger. The machine is then used to assist the operation when the turbocharger is in compressing mode, i.e. motoring the turbocharger, and generating power when the turbocharger is in turbine mode.

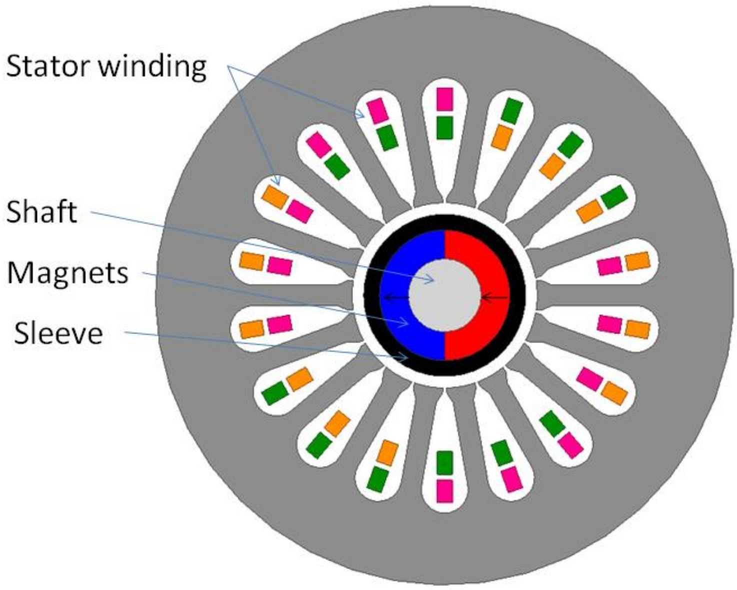


Fig. 2. Cross-section of the SPM machine.

TABLE I
DESIGN PARAMETERS OF SPM MACHINE

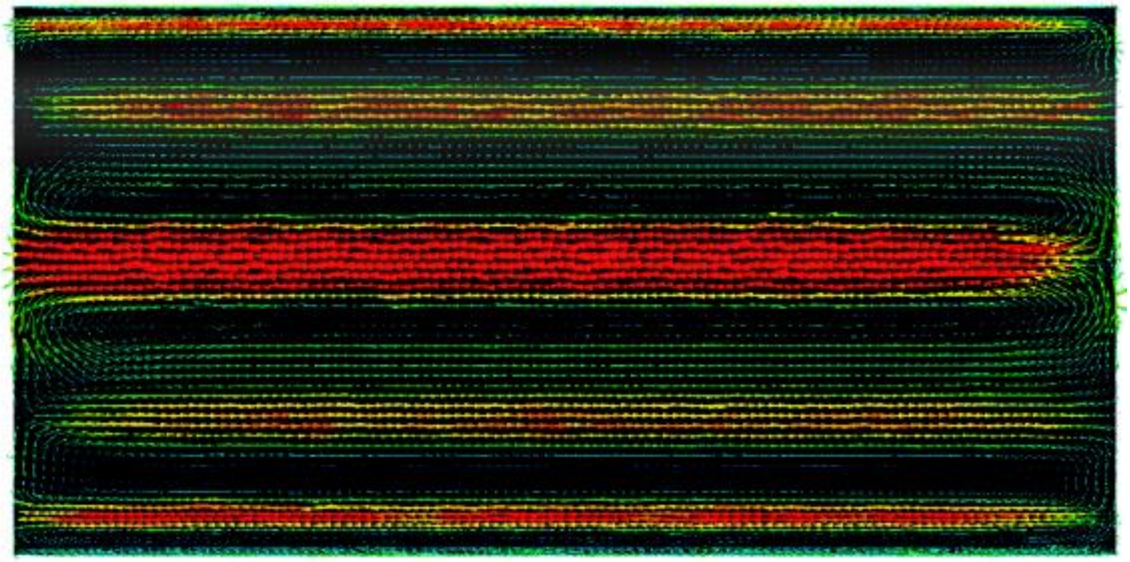
Unit	Quantity	Value
kW	Rated power	12
rpm	Rated speed	80000
A	Rated current	100
V	Rated voltage	48
Nm	Rated torque	1
kW	Rated power	20
-	Stator slots	18
-	Rotor pole pairs	1
-	Number of phases	3
mm	Stator outer diameter	100
mm	Stator inner diameter	32
mm	Airgap	2
mm	Axial length	56

s/m	Magnet electrical conductivity	1162800
s/m	Sleeve electrical conductivity	1820000

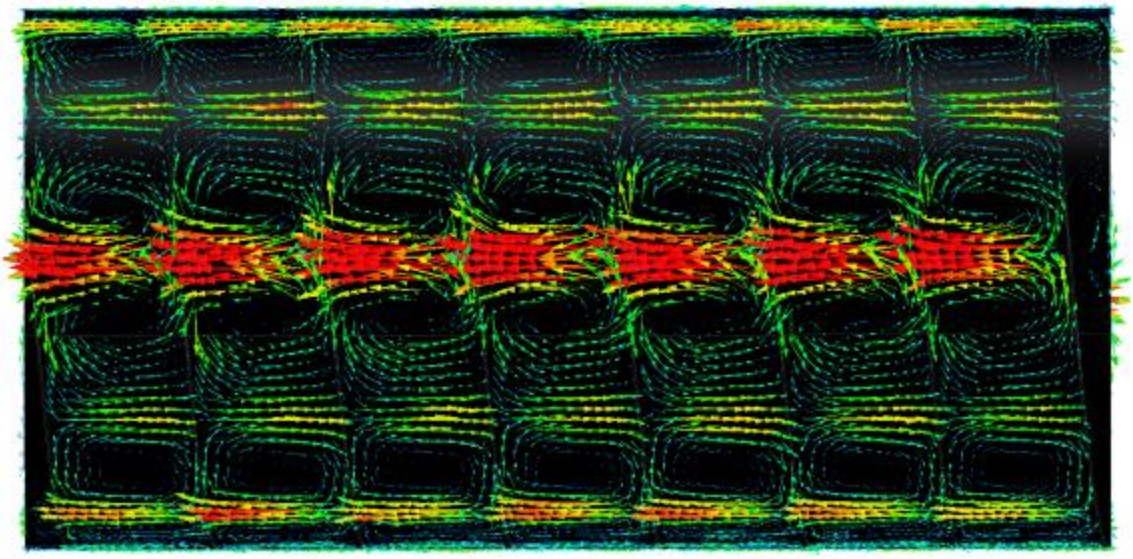
1.4. Electromagnetic Analysis

A 3D FEA simulation has been conducted to study the proposed helical sleeve. The machine speed has been set to 80000rpm. Three-phase sinusoidal current waveforms with a peak of 100A and frequency of 1333.33Hz have been injected in the winding. Thus, the simulation takes in consideration the space and time harmonics.

Fig. 3 shows the eddy currents distribution and circuits in a conventional sleeve and a helical sleeve with 7 turns. Similar to the axially segmented sleeve, the helix sleeve cuts the eddy current circuits axially and therefore leads to lower eddy current losses. The total losses of the sleeve and magnets in the conventional sleeve are 7.85W, whereas the total losses in the helical sleeve rotor with ten helical turns are 4.5W.

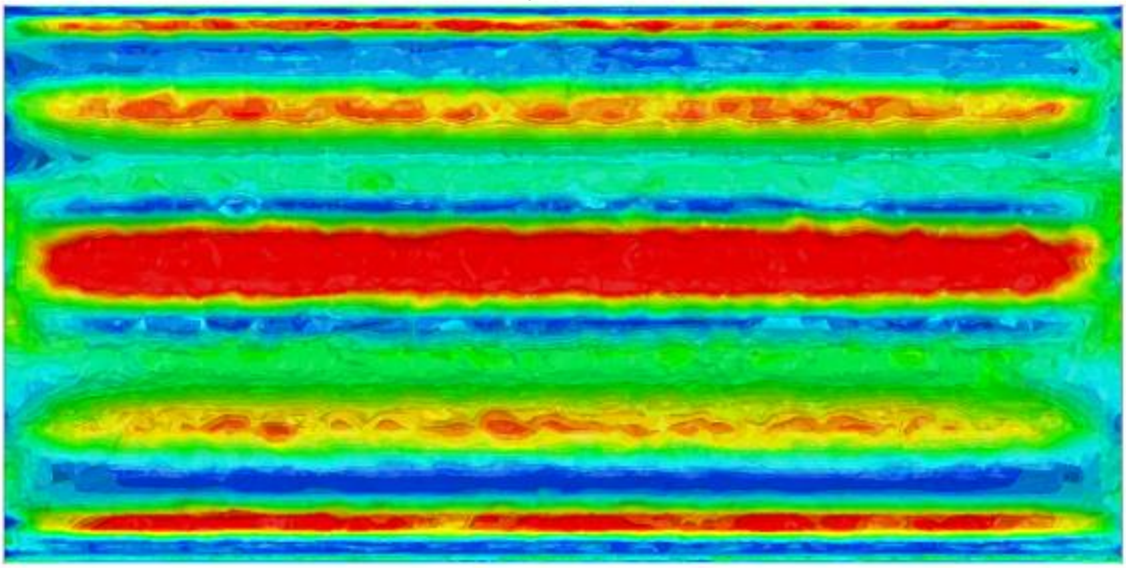


Conventional sleeve

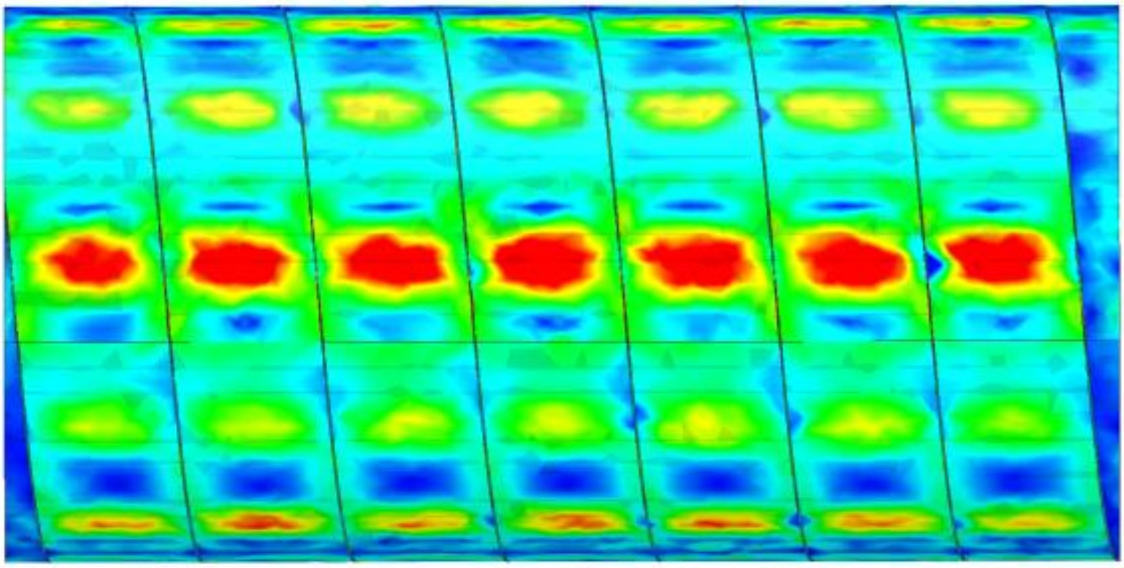


Helical sleeve

(a) Eddy current circuits



Conventional sleeve



Helical sleeve

(b) Eddy current distribtion

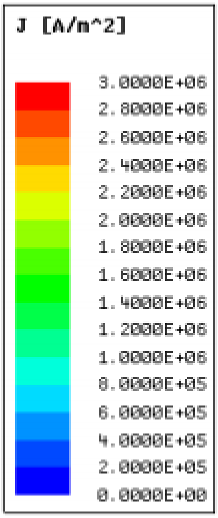


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Fig. 3. Eddy current circuits and distribtion in convetional and helical sleeves.

To investigate the effect of the pitch of the helical sleeve on the rotor loss, a different number of helix turns and hence turn thicknesses were used for the same machine. The results are shown in Fig. 4. The presented results are normalized, 1 is the loss of the conventional sleeve (no helical turns).

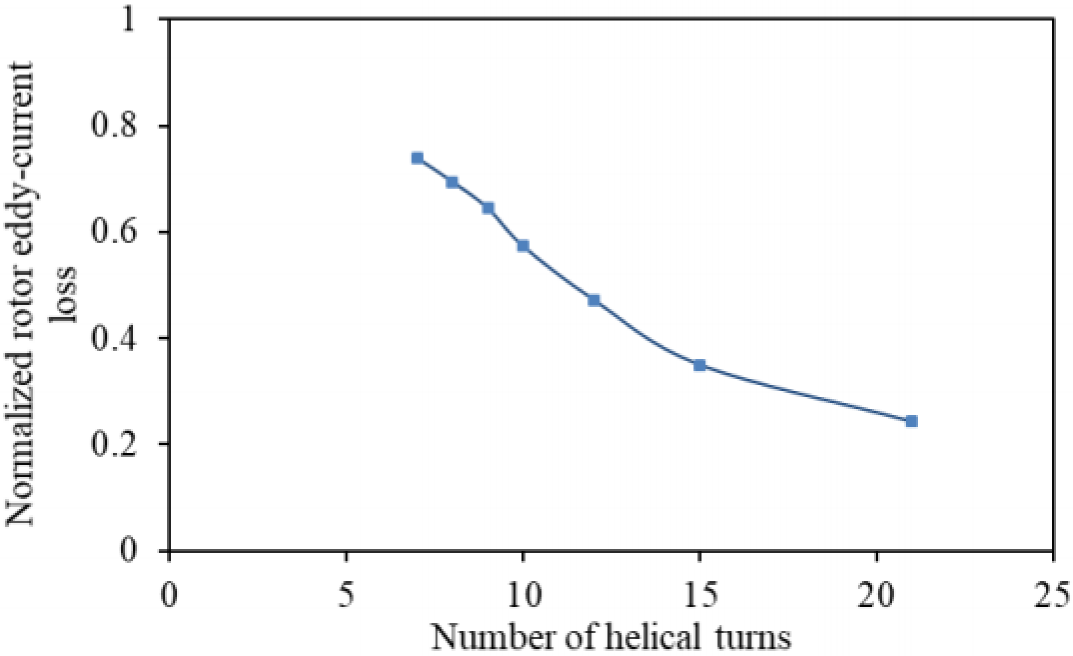


Fig. 4. Rotor eddy current loss versus the number of helical turns, normalized to 1 (the loss of the conventional sleeve without helical turns).

Considering Fig. 3, it can be seen that increasing the number of helical turns leads to an initially linear and then exponential reduction of the rotor eddy current loss. This is different from axial sleeve segmentation which results in an exponential reduction [17]. The reason is due to the helical path of the spring based sleeve allowing an axial current path length greater than the width of the spring cross section. However, when the spring pitch is reduced, this effect is quickly reduced and the spring more closely approximates an axially segmented sleeve. Overall, the helical sleeve results in significant reduction of the rotor eddy current loss.

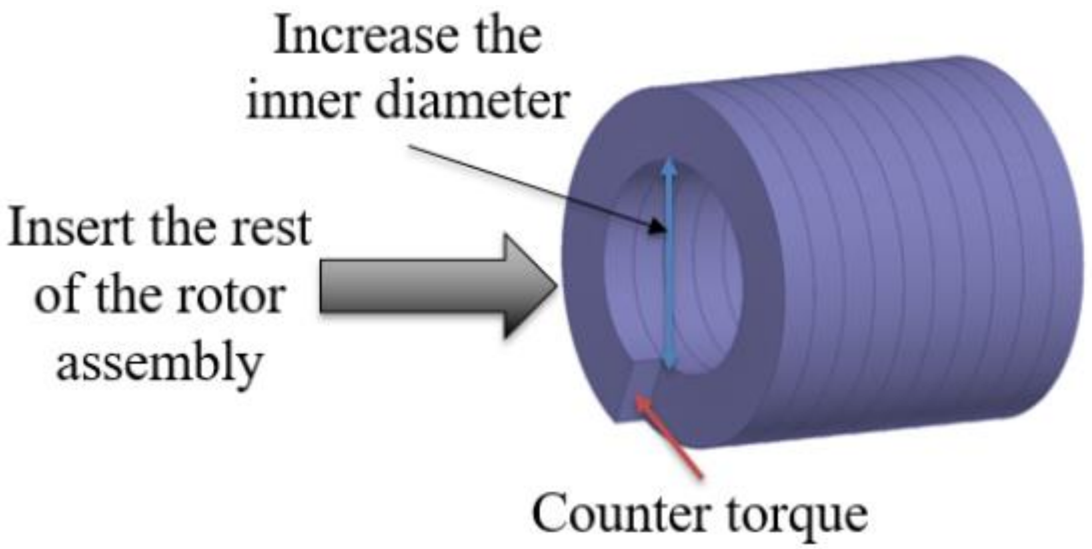
1.5. Assembly

In addition to the electromagnetic advantage, the helical sleeve offers a simplified assembly method compared to the traditional sleeve assembly. In particular for a high interference fit, the traditional assembly method consists of a combination of heating and cooling the assembled components and press-fitting the assembly. The helical sleeve can be assembled more easily since essentially it behaves like a torsion spring. By applying a counter-torque on the helical sleeve, the diameter of the sleeve will increase allowing the rest of the rotor assembly, i.e. magnet and shaft, to be inserted easily without the need for thermal changes or press-fit. Similarly, applying a tightening torque on the helical sleeve results in reduction in the diameter of the sleeve and hence an interference fit. Finally, a means of fixture such as industrial adhesive can be applied on the end-turns of the sleeve to fix the sleeve structure.

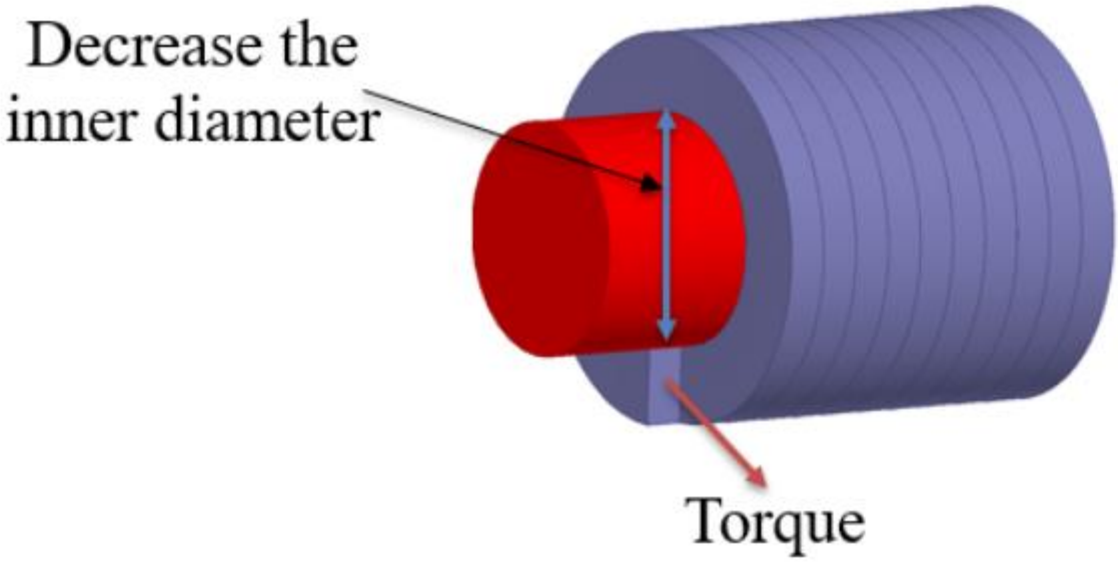
The governing equation for the changes in the inner diameter of the helical sleeve is [18]:

$$ID_{new} = ID_{original} \frac{N}{N+REV} \tag{1}$$

Where ID_{new} is the new inner diameter resulting from the applied torque, $ID_{original}$ is the original inner diameter of the sleeve, N is the number of turns of the sleeve, and REV is the number of revolutions of one end of the sleeve relative to the other as a result of the applied torque. Fig. 5 illustrates the assembly process.



(a)



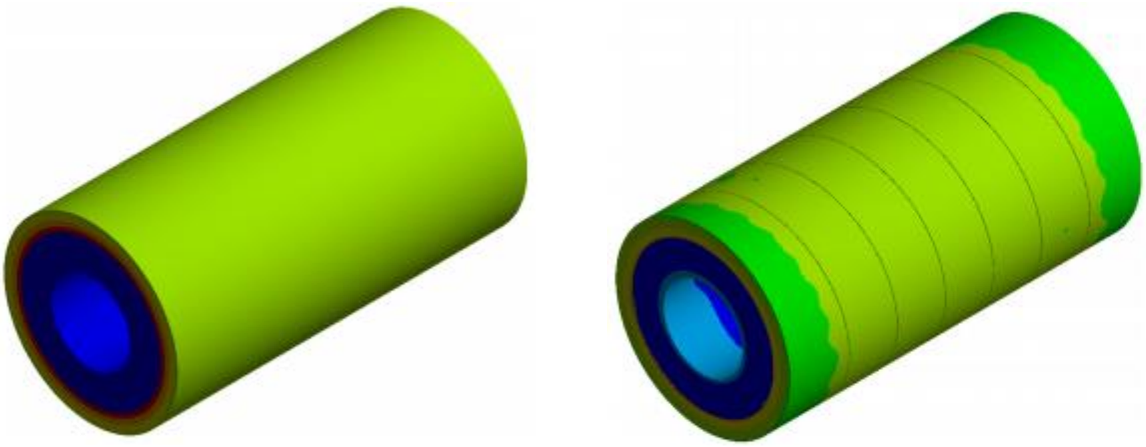
(b)

Fig. 5. Helical sleeve assembly.

1.6. Mechancial Analysis

Structural analysis of a high-speed rotor with conventional and helical sleeves has been conducted and compared to evaluate the mechanical integrity of the helical sleeve. A load condition of 50krpm rotational speed was applied. Boundary conditions of fixed support at the magnet inner surface and fixed axial displacement at the rotor ends were applied. Finally, an interference fit between the sleeve and magnet of 0.05mm was used.

The mechanical stress and deformation of the sleeve and magnet of both conventional and helical sleeves are shown in Fig. 6 and Table II lists the stress in different rotor parts. It can be seen the stress in PM and sleeve is similar in both rotors. Higher stress is found in the end-turn of the helical sleeve, as well as the higher stress on the PM surface at the gaps between the sleeve turns, however, similar to the axially segmented sleeve, the gaps between the helical turns can be eliminated by manufacturing the helical sleeve with closed turns, i.e. no gaps between the turns. The mechanical behavior of the helical sleeve is then very similar to a conventional sleeve.



(a) Conventional (b) Helical

Fig. 6. Equivalent (von-Mises) stress distribution.

TABLE II
EQUIVALENT STRESS (MPA) IN DIFFERENT ROTOR COMPONENETS

Component	Conventional	Helical
Sleeve outer surface	292	307
Sleeve inner surface	440	433
PM outer surface	35.5	22
PM inner surface	60	57.5
Sleeve end-turn	-	500
Magnet at sleeve gaps	-	75

1.7. Conclusion

A helical sleeve has been proposed to provide easier assembly and a reduction in eddy-current loss for high-speed permanent magnet machines. Similar to sleeve segmentation, electromagnetic analysis showed an increasing reduction in the total eddy-current loss as the pitch of the helical sleeve was reduced. Mechanical stress analysis showed similar stress levels in both the sleeve and magnet with small increase in the sleeve end-turns and in the magnets at the gaps between the turns.

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