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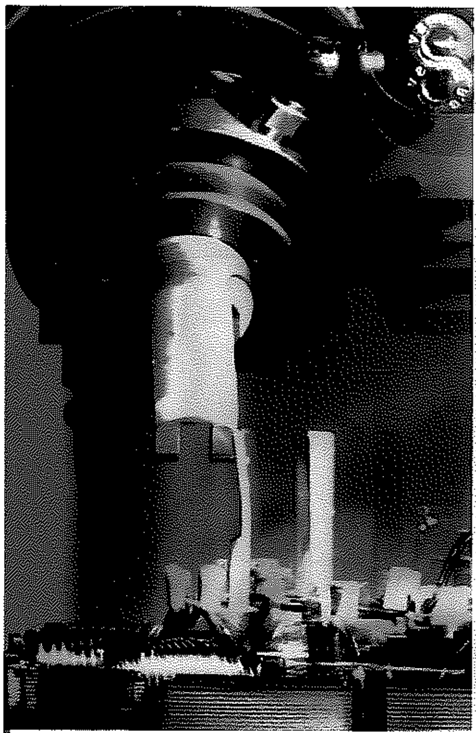

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Needle winding technology for symmetric distributed windings

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***Abstract*— This paper focuses on the construction and application of an automated needle winding machine for distributed windings and the accompanied adaption of the stator required to insert the conductors into the stator slot. In addition to possible advantages of this technology, in this contribution it is evidenced that the modification of the stator geometry does not cause any drawbacks avoiding the assembly of more compact and efficient motors. Therewith, several disadvantages of the semi-automated pull-in procedure like high production effort and inflexible costly machinery could be overcome. The proposed needle winding technology is promising, compared to conventional winding technologies to reduce the size and form of the winding end and offers new possibilities to decrease the axial height of the winding end due to the end caps which form outwards bended arching winding ends. This could pave the way to more compact and shorter electrical motors with increased efficiency.**

Keywords — Electrical machines, Winding technology, Needle winding, Electric traction drives

I. INTRODUCTION

The electric drive comes increasingly into the focus of research as a traction drive for urban vehicles. It can represent a serious long-term substitute to the internal combustion engine in the urban traffic. Rotational speeds beyond 20,000 rpm and high power densities in comparison to other machine topologies provide high efficient drives [1]. In order to meet these stringent requirements, permanent magnet excited synchronous machines with V-shaped buried magnets (VPMSM) and distributed windings are employed [6]. For various stator- and winding topologies there exist different techniques to wind the stator's windings. Depending on the geometry and the applied winding technology the copper fill factor and the height of the end windings can vary, and thus have a significant influence on the machine's size and copper losses. The increasing demand for such electrical machines requires low-cost technologies for automated manufacturing providing high copper fill factors and small end windings.

Conventional automatic winding machines can be distinguished in three technologies. Needle winding technology, flyer winding technology and linear winding technology [2]. For these winding processes the teeth of single-tooth windings are wound individually. Usually with these machines orthocyclic windings can be placed into the stator slot [2], that theoretically allows copper fill factors of up to 60 % [2]. Major drawback of the actual automatic winding machines is that stators constructions with inwards opened slots can merely be wound with single concentrated windings. Machines with such concentrated windings contain many harmonic waves in the air-gap field [3]. It can be stated that the more harmonic field waves penetrate the ferromagnetic material, the higher the iron losses can be expected [4]. Since iron losses increase disproportionately with the frequency [4], distributed windings for high speed machines can be beneficial.

II. CHALLENGE OF THE WINDING PROCESS

According to the state of the art, stators with distributed windings are fabricated using the pull-in procedure. Therefore, the windings are constructed on a coil carrier and subsequently pulled into the stator slot [3]. Depending on the stroke speed of the used hydraulic cylinder and the length of the stator the slot can be filled with one side of the coil, respectively the whole coil or even the entire winding, with simultaneous insertion of slot closing wedges is possible. The basic principle is based on reducing the coil sides to less than the slot width and thus they are protected against the edges of the slot openings which can damage the conductors while pulling them into the slot with Positioning and protecting the conductors against the edge of the slot is realized by polished steel profiles, also called pull in needles. These needles are adapted to a machine cross-section and a length of the machine The coils are wrapped around the needles automatically or hung over them manually according to the winding scheme. Often, the coils are positioned so that they are not centrally located in the stator. At the exit side the coil ends are arc-shaped beyond the stator cross section and thus cover neighboring empty slots. Therefore, intermediate form operations must be done enabling further pull-in procedures.

Stators manufactured with the pull-in technology show however various drawbacks. There is the demand to rework the end windings in a time consuming procedure. Protrudent end windings have to be formed and pressed in order to fit the stator in the designated motor housing. Often required winding lacing increases the workload and the danger of damaging the insulation during the winding process. Wiring up the connecting conductors automatically poses to be troublesome or even has to be done manually. Due to large wire bulges in the end winding the required wire length exceeds the necessary one using different winding technologies. This increases the copper material expenses. Furthermore the pull-in technology requires costly special machinery which may not be adjustable and therefore only applicable for a limited variety of stator constructions. Usually, this procedures generate wild windings, that yields copper fill factors of approximately 43 % [2].

Actually there are no automated winding machines in the market for winding stators without covering the neighboring empty slots. The slots that are not wound in the current winding step have to be kept open in order to enable the insertion of windings in the subsequent winding cycle. A technology is required, that realizes an automated stator winding for symmetric distributed windings that offers a high degree of automation at low initial invest to increase output.

Hence, this paper focuses on the construction and application of an automated needle winding machine and the associated adaptation of the stator that is required to insert the wires into the stator slot. Essential geometric modifications of the stator may not cause appreciable deterioration of the machine characteristics. Therefore, the accompanying changes in the characteristics of the machine are examined. In addition, increasing the copper fill factor and decreasing the end windings in size by the winding technology will be discussed.

III. Approach

The torque of an electrical machine depends on the copper area in the slot and the magnetic flux density in the air gap. Therefore, it is essential to maximize the copper cross sectional area. Furthermore small end windings reduce the copper losses, which yields to increasing machine efficiency. Distributed windings are used to reduce the harmonic content of the air gap field. Especially in high speed machines harmonic fields generate torque ripple, structure-born sound radiation, additional iron losses and other parasitic effects.

A. *Needle winding technology*

The technology for pull-in windings does not yet have the potential of filling up the stator automatically. Automated needle winding machines are used to wind single teeth, but this technology can be adapted to wind an electric stator winding with distributed winding topologies.

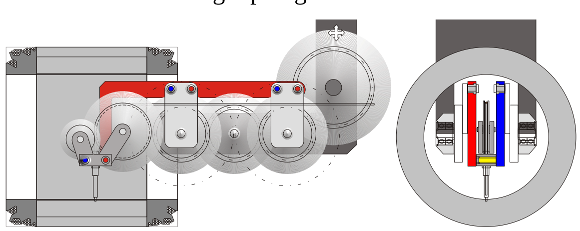


Fig. 1. Needle winding machine invented by *Aumann GmbH*.

In the case of distributed windings the winding step is more than one slot. That means the needle winding machine has to be able to cross several slots between inserting the wire into a slot without covering the remaining slots in which windings still have to be inserted. The industrial project partner *Aumann GmbH* is responsible for the construction of the projected needle winding machine (figure 1).

1) *Setup of the needle winding machine*

The needle winding machine (figure 1) is used to fill up stator slots with a distributed winding. It consists of a winding head that is translatorily movable in the longitudinal or the transverse direction, a needle carrier system with a wire outlet nozzle and wire guidance. The needle carrier system is controlled by a parallelogram guidance and a drive unit, in which the movable block of the needle carrier system can be rotated along a whole virtual circle circumference. The wire outlet nozzle remains pointing in the direction of the centre of the virtual circle and defines a virtual pivoting point.

2) *Filling up the stator slots with winding conductors*

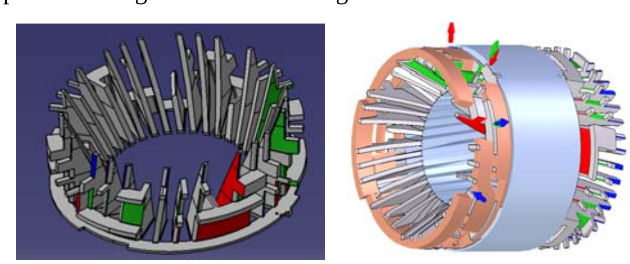
In order to place the winding conductors in the stator slots, the conductors of the first winding are fixed in the end cap and subsequently inserted with the needle winding system into the designated slot. With this process the wire outlet nozzle places the wire inside the slot along the length of the stator without penetrating the slot. In order to prevent damage of the wire it has to be ensured that the slot opening is sufficiently wide to insert the particular conductors.

This process avoids that the wire bundle in the first track of the end caps of one pole covers up the slots and tracks of the remaining wire bundles corresponding to the designated winding step. After inserting the first coil the other poles of the winding are set in place. Depending on the number of pole pairs the insertion process of the coils is repeated.

The entire winding phase is inserted during a winding cycle without separating the winding electrically. The parallel wires or stranded conductors can be placed into the stator and complicated electrical connections of individual coils with a high number of wires is avoided. As shown in figure 2, the configuration of the end caps prevents the end windings covering the slots on the machines axial front surface. Thus, sufficient space remains in order to insert the other coils of the distributed winding. These are one by one set in place. After inserting the last wire bundle, depending on the structure of the end caps, the slots can be covered completely.

3) *Structure of the end caps*

As shown in figure 2.(a), the end caps consist of a base plate and a slim lamella structure form the axial surface of the stator. The end caps hold the tracks which map the paths of the phase windings in the end windings.



(a) Lamella structure of the end caps. **(b)** End caps and stator.

Fig. 2. Structure of the end caps that create the winding head.

The structure of the end caps, as shown in figure 2.(b), enables the outlet nozzle of the needle winding system the consecutive insertion of single windings into the winding tracks. These tracks of the end caps pose as guidance from slot to slot of the stator core for the wire and prescribe the shape of the end winding. The lamella structure is configured in order to consecutively insert all poles of one phase and still keep space for the remaining coils. The flexible design of the end caps enables the insertion of a zoned and pitched winding as well as the implementation of a skewed stator slots. As shown in figure 2.(b), the lamella structure can be adapted to follow the slot exit angle. Depending on the number of slots per pole and phase of the machine, according to (1), the end caps can be adjusted to fit various numbers of stator constructions with different winding topologies.

4) Results

The introduced needle winding technology to wind stators with distributed windings is promising, compared to conventional winding technologies, to reduce the size and form of the end winding. Large wire bulges that develop for example when using the pull-in procedure and have to be formed and/or secured with resin can be avoided. The proposed technique also offers interesting possibilities to decrease the axial length of the end winding due to the end caps which form outwards bended arching end windings. This could pave the way to more compact and shorter electrical motors with increased efficiency. Furthermore, the electrical terminals are positioned more accessibly and the separate phases are better insulated by the end caps. The introduced winding technology decreases the required amount of copper compared to the pull-in procedure. This reduces the cost as well as the copper losses. Additionally thicker wires can be processed. The mountings of the phase ends can be implemented at one of the front axial surface of the end caps. These terminals can be used to interconnect the phases and to create a star-delta-connection.

Due to larger wire diameters, when compared to the pull-in procedure, the conductors can be placed more parallel inside the slots. Therefore, a copper fill factor of more than 50 % is aspired. At present orthocyclic windings can not yet be fabricated with the discussed winding technique. However, currently it is subject of the research to develop a technology that enables placing individual wires with high precision into the slot.

B. Adaptation of the stator geometry

In order to wind the designed motor with the introduced needle winding technology and to benefit from the discussed advantages, the stator geometry has to be adapted. Particularly, the slots, respectively the slot openings, have to be geometrically adjusted to fit a safety margin and enable inserting the windings into the slots without destroying the the conductors insulation system. However, every modification of the stator geometry immediately influences the electromagnetic characteristics and therefore the performance of the motor. To evaluate any differences in the motor performance the initial motor as well as the modified geometry are presented. Different operating points of both motor models are simulated with the institute's in-house software package pyMoose, evaluated and compared.

1) Introducing the initial motor

Figure 3 shows the geometry of the examined motor topology. It is a permanent magnet excited synchronous machine having m = 3 phases, N = 36 slots and 2p = 6 poles. The slots per pole and phase is

$$q = \frac{N}{2 \cdot p \cdot m} \quad (1)$$

according to (1) this results in q = 2 for this machine. With the supply voltage U_{Bat} of 100 V the motor can continuously operate at the maximum torque M of 100 Nm and a maximum speed n up to 10,000 rpm. The output power rating P is 30 kW.

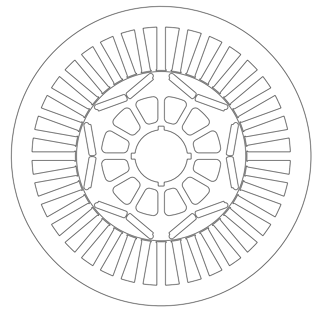
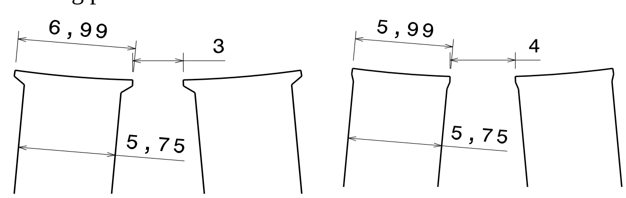


Fig. 3. Geometry of the initial motor.

The motor's supply voltage influences the winding construction. The low voltage, as it is used in this project, causes high electrical current and consequently leads to a large wire cross sectional area and a low number of windings. In this case the number of windings is set to 1, since more windings would increase the induced voltage and thus limit the range of speed below the specified 10,000 rpm.

2) Geometric Adaptation of the slot opening

A certain slot opening is required inserting the wire into the stator slot without damaging its insulation. The previously defined stator geometry has to be modified, since the 3.0 mm slot opening (figure 5.(a)) is not sufficient for the automated winding process.



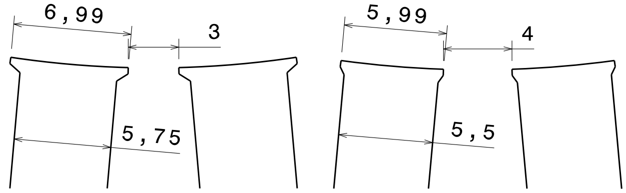
(a) Stator tooth without modification. **(b)** Stator tooth with modified tip.

Fig. 4. Various stator tooth geometries of the initial and modified motor.

In addition to the required space for the 3.0 mm conductors, specified by the winding machine producer Aumann GmbH, a safety distance of 0.5 mm has to be impinged. This distance prevents contacting the wire and the stator during insertion of the winding conductors. In collaboration with Aumann GmbH it was decided to set the distance between the tips of the stator teeth to 4 mm (figure 4.(b)).

3) Geometric adaptation of the tooth width

Increasing the gap between the stator teeth edges, the tip size to the width of the stator tooth will now be discussed. Since a wider stator tip is necessary to protect the windings mechanically, the stator tooth width hast to be reduced. The modified stator tooth and stator tip is shown in figure 5.(b).



(a) Stator tooth without modification. **(b)** Stator tooth with modified tip and width.

Fig. 5. Various stator tooth geometries of the original and modified motor.

The width of the stator tooth is reduced by 0.25 mm to 5.5 mm. This increases the copper cross section from 199.0 mm^2 up to 206.5 mm^2.

4) Evaluation of the new stator design

The modification of the stator tooth geometry has several effects on the motor characteristic. A wider slot opening leads to an increasing pulsation of the air gap flux. The copper cross sectional area A_{CO} in the slot is increased from 199.5 mm^2 up to 206.5 mm^2 by reducing the stator tooth cross section, which results in a higher flux density and raised the saturation level in the teeth. Therefore, potential changes in the cogging torque, as well as in the iron- and copper losses, have to be evaluated and compared to the initial geometry.

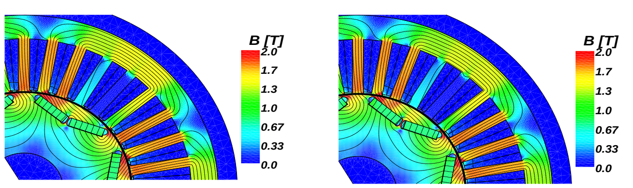
TABLE I. CURRENT DENSITIES OF DIFFERENT OPERATION POINTS

Operation Point	**Current Density**	
	J_d	J_q
1- partial load	3 A/mm^2	-3 A/mm^2
2 - full load	4 A/mm^2	-5 A/mm^2
3 - field weakening	1 A/mm^2	-4 A/mm^2

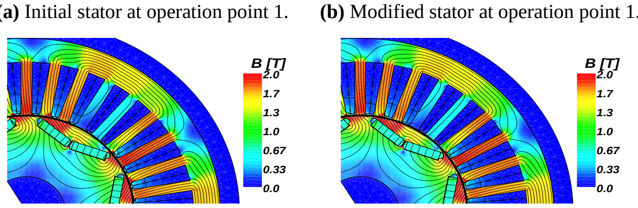
Therefore, three different operation points have been chosen (table I). The operation points, the partial load, full load and field-weakening range are simulated and the magnetic flux densities as well as the torque curve are evaluated.

a) Evaluation of the magnetic flux density distribution

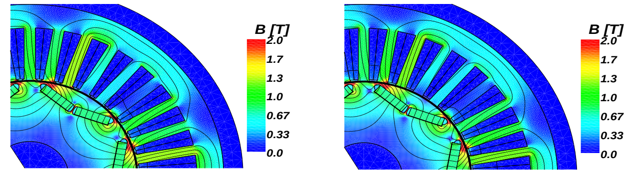
In figure 6 the distributions of the flux density B of the initial and the modified geometry at the operation points are plotted. At partial load in both geometries neither the stator teeth nor the stator joke with a flux density around 1.6 T are highly saturated excluding the stator tips and the rotor bridges around the magnets in which the flux density exceeds 2 T.



(a) Initial stator at operation point 1. **(b)** Modified stator at operation point 1.



(c) Initial stator at operation point 2. **(d)** Modified stator at operation point 2.



(e) Initial stator at operation point 3. **(f)** Modified stator at operation point 3.

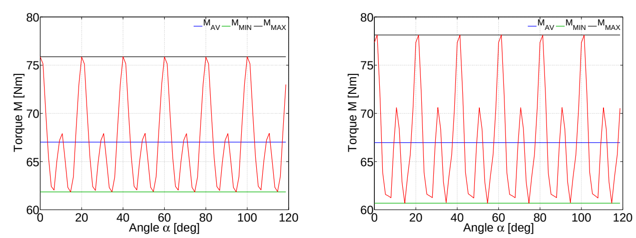
Fig. 6. Magnetic flux density of the original and modified motor.

High torques require higher current densities leading to flux densities above 1.7 T in the stator joke and teeth. In figures 6.(c) and 6.(d) these regions in both geometries are saturated with flux densities beyond 1.8 T. Comparing figures 6.(c) and 6.(d) shows, that the reduced tooth width of the modified stator geometry leads to a marginally higher magnetic flux density.

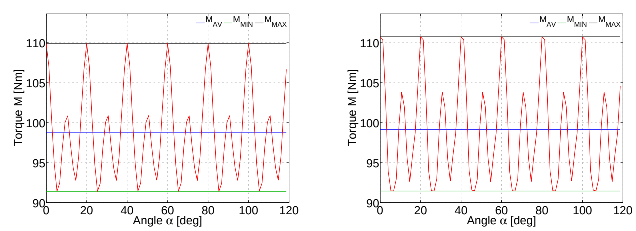
In figure 6.(e) and 6.(f) the magnetic flux density decreases to 1.1 T. Due to the high load angle the stator flux has the opposite direction as the rotor flux. This appears at high frequencies and speeds. Therefore, it can be assumed that amplified harmonic content and parasitic effects caused by the high angle between rotor and stator flux will occur [5].

b) Evaluation of the torque characteristics

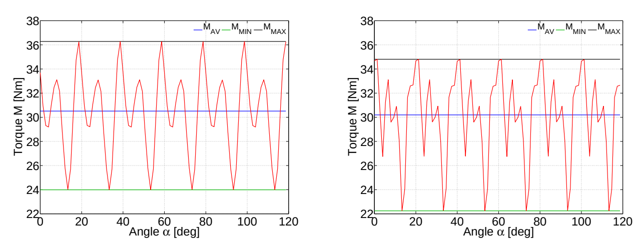
In order to conduct a quantitative comparison of the two evaluated geometries the torque curves in the operating points defined in table I are examined. Besides the average torque M_{AV} the time dependent component m_{ripple} is part of the evaluation (figure 7).



(a) Initial stator at operation point 1. **(b)** Modified stator at operation point 1.



(c) Initial stator at operation point 2. **(d)** Modified stator at operation point 2



(e) Initial stator at operation point 3. **(f)** Modified stator at operation point 3

Fig. 7. Torque with the initial and modified motor geometry.

The difference of the constant component of the torque quantity is in all operating points negligible. The absolute difference of M_{AV} amounts to 0.05 Nm in partial load operation (figure 7.(a) and 7.(b)). Also, due to widened slot openings in the modified geometry the torque ripple m_{ripple} according to

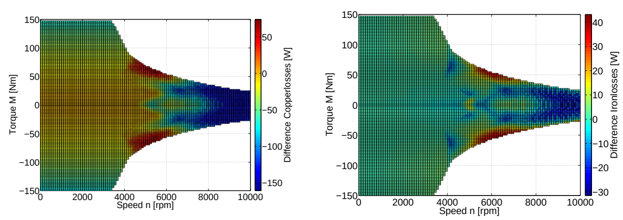
$$m_{ripple} = \frac{M_{MAX} - M_{MIN}}{M_{AV}} \qquad (2)$$

is amplified slightly from 21 % up to 26 %.

At higher loads the difference of M_{AV} does not increase significantly. In full load operation the torque differs as seen in figure 7.(c) and 7.(d) merely by 0.4 Nm. The ripple declines and increases from 18.7 % to 19.3 %. In field weakening operation the difference of the average torque is negligible. For both motors the ripple moment is quite high but the difference is insignificant again. Thus m_{ripple} rises from 40 % to 41.6 %. As shown in figure 7.(f) the torque curve of the modified geometry is distorted. This can be caused by the higher harmonics which occur in the field weakening range [5].

c) Evaluation of the loss characteristics

In order to illustrate possible deviances in the performance characteristics of the machine the iron and copper losses of each machine are calculated and the difference maps are generated. The losses of the modified geometry are subtracted from the losses of the initial one. The absolute difference is mapped onto the torque versus speed map.



(a) Difference map of copper losses.

(b) Difference map of iron losses.

Fig. 8. Differenz maps of losses of the original and modified motor geometry.

Comparing figure 8.(a) and figure 8.(b) it is apparent that only a marginal difference exist between the losses. Up to rotational speeds of 4,000 rpm, the losses remain the same. Between 4,000 rpm to 6,000 rpm and more than 50 Nm the simulation of the modified geometry shows less losses. Above 7,000 rpm the initial geometry seems to be advantageous. The comparison of the two loss maps shows, that the differences in the copper losses are more pronounced.

5) Results

The modification of the stator geometry to increase the slot openings enables bringing the windings into the stator with the proposed automatic needle winding machine. Differences regarding the saturation, the torque and loss characteristics of the machine are simulated and found to be negligible. Therefore the modifications of the stator geometry show no notable effects on the performance characteristics. Merely the losses are redistributed regarding the loss mechanisms.

IV. Conclusions

Using a needle winding machine for a stator with distributed windings affords the advantage producing high efficient motors with an automated technology. In addition this solution offers a high degree of scalability with a low initial invest. Increasing the output can be achieved by optimizing the winding process or adapting the stator geometry.

The pull in technology is limited to smaller conductor diameters due to the disordered wires. Crossings of thicker wires would damage the insulation during the pull-in process. With the needle winding technology the wire can be placed into the stator slot in a concentrated way, without the risk of damaging conductors insulation. For this purpose, only the slot opening was adapted. Possible differences of the machines characteristics provoked by the modification of the slot opening, that enabled the automated winding placement, were evaluated. Based on a simulative evaluation it has been derived that neither the saturation characteristic nor the torque and losses show significant differences. Combined with the introduced end caps, compact and efficient motors with distributed windings can be produced in small or medium series.

V. Acknowledgment

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