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Abstract

Electric motor for aircraft propulsion

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This paper deals with the mechanical construction process of an electric motor demonstrator of Mauritz Andersson's design. Several design issues have been addressed, primarily the winding of the coils, the fixation of the coils and how to connect the coils to the power electronics. Some mechanical parts have been constructed, and some preparations for creating the power electronics have been examined.

The coils have been manufactured by using enameled copper wire, winding it with a crank onto a winding tool. The coil have been fixated with adhesive and removed from the winding tool. Several different adhesives have been examined, where 2-component heat transfer adhesive from Fischer Electronics and Polyester resin ULTIMEG showed to be the most prominent ones. The layout of the winding tool have been given much attention, and the winding path of the enamelled wire have been carefully planned, which increased the number of revolutions from 76 to 90.

Handledare: Mauritz Andersson
Ämnesgranskare: Ladislav Bardos
Examinator: Hana Barankova
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1 Introduction

Electrification of air planes are highly relevant in today's society. The issues surrounding pollution are growing and environmental friendly air planes are required as a long term solution. Therefore, an electric motor demonstrator of Mauritz Andersson's design, which can be seen in Figure 1, is built within the framework of the course *Independent Project in Electrical Engineering*.

The purpose of the electric motor is to examine the possibility of electrifying an aircraft drivetrain. This generates high demands on the properties of the motor, in particular the power to weight ratio. The design of the motor is based on these conditions, and it is projected to have high torque and high power for its weight. Several different areas of the practical construction and the assembly process have been investigated.

In order to get the maximum torque from the motor it is essential to maximize the current, which generates the magnetic flux that turns the rotor. The current is limited by the heat generation from the resistive properties of the wire, as well as the cooling of the coils. Therefore good heat transfer properties and good airflow are desired.

The coils are wound externally, and afterwards fixed on the stator. This increases the efficiency of the winding process and allows the coils to be removed and replaced during the design phase while evading the need of replacing the expensive cobalt steel stator.

Some mechanical components are created and some effort has been made to plan the connection process for the coils and the circuit layout of the power electronics.

This paper will not investigate the magnetic flux, electrical properties or the design of the motor since this has been done by Mauritz Andersson.

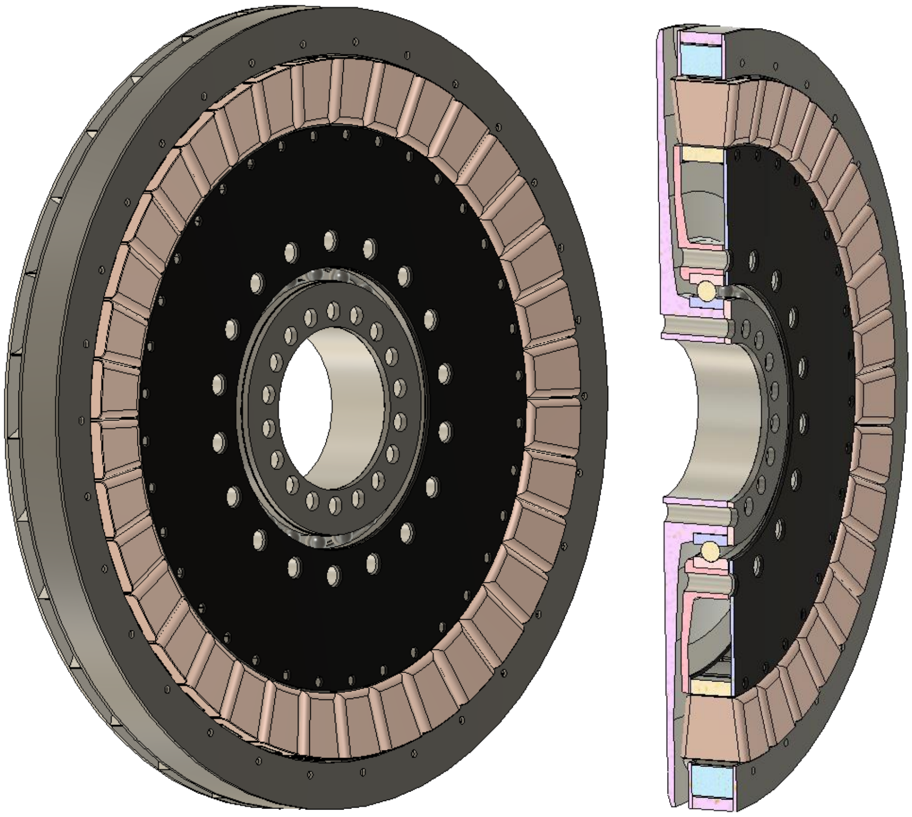


Figure 1: CAD drawing of the electrical motor, overview and cross-section.

2 Experimental procedure

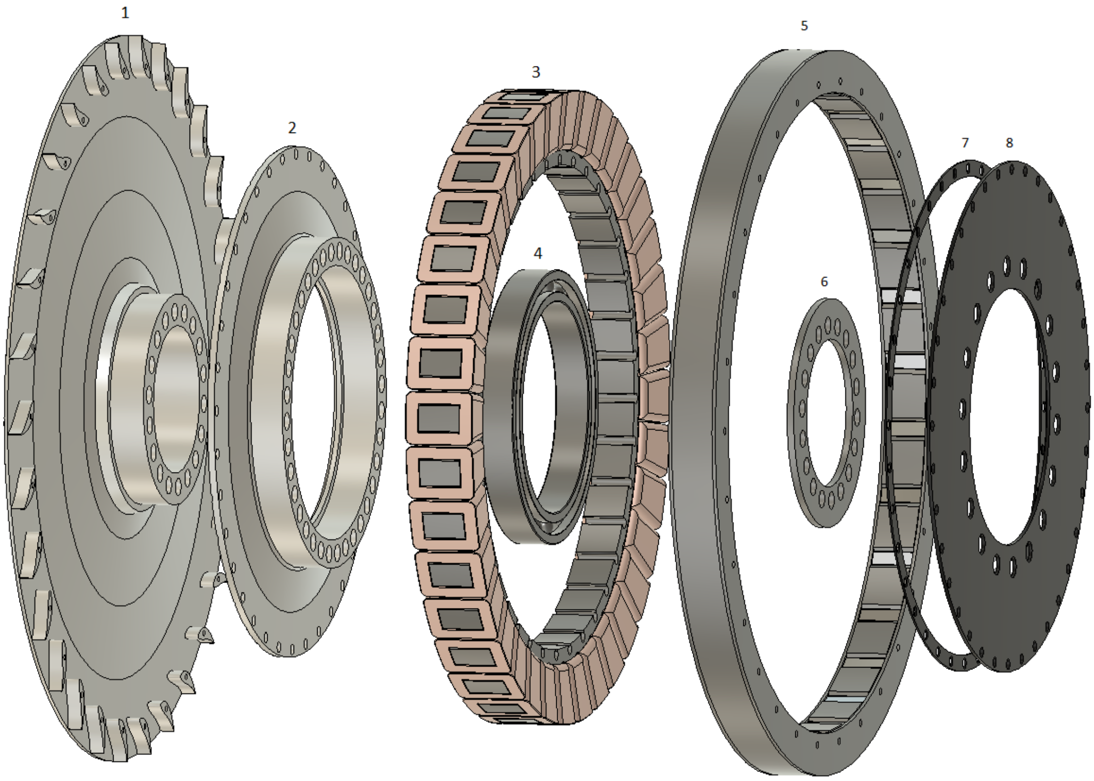


Figure 2: Exploded view of the electrical motor with numbered components. 1: Stator, 2: Rotor, 3: Cobalt-steel core with coils, 4: Ball bearing, 5: Magnets with carbon fibre plates, 6: Part for locking the ball bearing, 7: Distance plate for stator, 8: Distance plate for stator.

2.1 Winding tool

The winding tool was used as core for the coil, and the wires of the coil was wound around the tool to create the coil. When the wounding of the coil was finished, the coil has to be removed. This was achieved by for example splitting the coil into two parts or by using a thin plastic sheet on the short sides of the coil, where the thickness of the coil is not critical for the design. Each design was evaluated by using it to wind at least the inner half of a coil.

2.1.1 Aluminium tool

The aluminium winding tool is a copy of one of the coil segments of the cobalt steel alloy stator, see Figure 2, component 3. In order to simplify the removal of the coils, a 0.5 mm thick plastic stripe was placed on each short side of the winding tool. After the coil was wound, the stripe was removed and the tension of the wires in the coil was loosened, and the coil could be slid off the tool.

2.1.2 Plastic tool

The plastic tool was designed in the Solidworks 3D CAD software and printed in a 3D printer. It consists of two halves which together are a copy of one of the coil segments of the cobalt steel alloy stator, see Figure 3. However the difference is found close to the curve of the coil segment, where the plastic tool has a ladder design which allows the copper wire to close to perfectly advance from one layer to the next, without any excessive build up. The specific design was evaluated and any problems was corrected, after which a new tool was printed. This allow efficient design iteration.

2.2 Winding setup

In order to wind the coils efficiently a setup with a crank and a wire reel is needed. Both winding tool and wire reel need to be able to rotate freely, unless a breaking mechanism that tenses the wire during the winding of the coils is desirable. The winding setup consists of a back plate on which a wire reel and a crank was mounted on. The winding tool was mounted on the axis of the crank. This allows the crank to be turned while the wire reel is slightly tightened to the back plate which gives friction breaking of the wire. Where the axis of the crank penetrates the back plate a reinforcement consisting of two small metal plates, one on each side of the back plate, was installed to ensure a stable circular motion of the crank. The crank is constructed of a metal stripe with a hole in each end and two long screws that was fastened in each end of the metal stripe. The tool was fixed on the crank with a washer, which provides an outer limit for the coil. Nuts was used to fix the winding tool on the crank and the crank on the back plate. The setup was tested in both plastics and metal.

2.3 Fixation method for the coils

When the motor is turning there are magnetic forces acting on the magnets and on the iron, which originates in the coils. Although most force acts on the iron, some force is acting on the coils, and therefore they should be internally fixated. This was achieved by adhesive or resin. The adhesive or resin was applied between each layer of wires during the winding of the coil. The coil was left for at least 12 hours of curing. After the curing the coil was unwinded by hand and the sufficiency of the fixing was estimated.

2.4 Winding process

There are different ways to wind the coils, and attention needs to be given to starting position, ending position, number of windings for each layer and the transition from one layer to another in order to fit as many revolutions as possible in the limited space of one coil segment. This was practically done by using the winding tool and the winding setup. One coil was wound turn by turn and fixated according to the fixation method. When a few coils are cured and removed from the winding tool, the coils can be tested by placing them on the cobalt-steel stator next to each other. The distance between the coils was inspected visually, and the coils should be able to slide on and of the stator with ease, and also contain as many revolutions of copper wire as possible.

2.5 Connection and marking of the coil wires

Due to the high number of connections that are required on a limited space, the connection and splicing of the coil wires should be as small as possible. Two options was tested when connecting the coils, primarily the coils can be connected with heat shrinking solder sleeves. Either the wire needs pre heating to vaporize the enamelled coting by a gas torch, or the soldering results in full connectivity in itself. Regular clamping sleeves was tested as a second option. The wire is pre heated to vaporize the enamelled coting and the clamp was attached to the wire. A shrinkable tube was shrunk over the clamping sleeve to isolate it.

To keep a tidy and easily workable design evident marking of the 72 wires that connects the coils to each other and the power electronics are needed. To achieve this about 5 millimetres of white shrinking tube can be shrunk over key positions of the coil wires inner and outer end. The white shrinking tube can be marked with a number from 1 to 72 with a permanent marker. The position of the coil wire together with the corresponding number should be documented.

2.6 Distance plates for stator and rotor

Between the stator mechanics and the cobalt-steel core a non-metal distance is desired to separate the magnetic flux in the cobalt-steel from the aluminium stator to prevent eddy-currents, see Figure 2, component 7 and 8. The same function is desired for the rotor where the magnets are to be separated from the aluminium rotor mechanics, see Figure 2, sides of component 4. The distance plates in the rotor also have the function of fixing the magnets. The distance plates was cut out of carbon fibre epoxy laminate with a CNC milling machine to achieve three ring segments. A 3D-printed drilling guide was glued to the ring segments. The screw holes are drilled with a drill press according to the drilling guide.

2.7 Mechanical appliances and components

The ball bearing needs to be securely fitted on the motor. The rotor fixes the ball bearing on one side, and a suggestion of a part for locking the ball bearing on the other side was designed. The part is intended to cover the inner rim of the ball bearing, without interfering with the rotational movement of the rotor.

2.8 Experimental board

The selected motor drivers, IRAMAX30TP60A, which are controlled by an Arduino M0 Pro, need a circuit board. To simplify the wiring and soldering process, a circuit board CAD file with the circuit was created in the EAGLE PCB Design Software. The IRAMAX30TP60A was manually added as a component library since it did not exist among the components in the standard EAGLE library. The layout of the schematics was taken from the IRAMAX30TP60A data sheet and combined with the layout of the Arduino board. The Eagle CAD file is intended to be used as a guide to manually solder an experimental board. Due to the circuit design, the experimental board should have soldering traces that stretch from one end of the board to the opposite side. The soldering traces are cut with a knife in any places where a connection is unwanted.

3 Results and Discussion

The mechanical shop wasn't able to mill the stator and rotor before the end date of the project and therefore some of the planned experiments could not be performed.

3.1 Winding tool

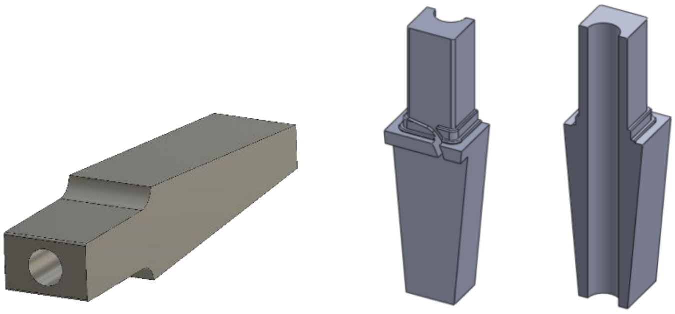


Figure 3: Winding tool, aluminium and plastic.

3.1.1 Aluminium tool

The aluminium tool gave decent coils, however the end of the coil at the curve of the tool resulted in a mess. The wire had to be wounded over itself in an unordered fashion which resulted in a loss of turns. This resulted in fewer revolutions compared to the plastic tool, see Appendix 6.2.

3.1.2 Plastic tool

The initial plastic tool was better at creating a decent end on the coil, since the wire was fixed with adhesive before it was removed from the tool. The improved end of the coil resulted in it being able to fit tighter onto the stator, and there was about a millimetre of space between the outer end of the coil and the edge of the stator. Therefore the plastic tool was extended since there was space for another set of turns. This was tested and worked well, the outer edge of the coil lined up well with the outer edge of the stator. For the inner end of the coil, a groove was added as a starting point for the inner end of the coil. For uniformity and to avoid any entanglement between the turns the ladder design was applied to the short sides of the tool as well. Where the pitch was allocated, there was a problem with it being too steep, which added up to an unwanted pitch in some places where the wire was planned to be straight. This could be prevented with a less steep pitch, for example that half the pitch is assigned to each short end of the coil. This however needs to be tested thoroughly since it might lead to new problems.

3.2 Winding setup

The initial winding setup with a plastic back plate was too unstable, see Appendix 6.1. While winding the coils with a little friction brake applied the plastic plate occasionally bent as much as two centimetres close to the crank. The back plate in 3 mm thick iron was immovable and worked perfectly for the task. The reinforcement for the crank axis worked well and the crank was easily rotated.

3.3 Fixation method for the coils

Several glues with good adhesion to metals, since the wire is made of copper, was tried out. However the adhesives did not fix the wire sufficiently, which was attributed to the coating of the copper wire. Investigation of the datasheet for the copper wire showed the coating as polyurethane, which is the material the adhesive needs to fix. The most prominent adhesive option was a two component epoxy based heat transfer adhesive. It had sufficient, but lower than desired, fixing properties on polyurethane. Due to a high price per gram it is not very cost effective. Polyester resin was tried out, with good results regarding fixing properties. The structural integrity was a problem during the required heat curing, the coil deformed in some extent. This would not be a problem if the design was final, and the heat curing could be done with the coil on the stator. However a prototype with replaceable coils are desired. For the list of adhesives tested, see Appendix 6.3.

3.4 Winding process

The winding process was preformed both with the aluminium and the plastic tool.

3.4.1 Aluminium tool

The removal of the coils was tried without the plastic stripes, and proved to be close to impossible. After the first layer the coil was so tightly locked to the aluminium tool that excessive force was needed to remove it, despite the use of both separating Kapton tape and PTFE lubrication.

After a few attempts a decent coil was wound with the aluminium tool and with the plastic stripes for removal. For exact revolutions see Appendix 6.2.1.

A problem was found with the length of the coils. This was adjusted with a 0.5 mm thick plastic sheet placed at the end of the winding tool. This gave a coil that fitted well on the stator with a total of 76 revolutions. For exact number of revolutions of each layer, see Appendix 6.2.1.

3.4.2 Plastic tool

The plastic tool was a big improvement in comparison to the aluminium tool. All the layers could be wound in an orderly fashion and the time to wind a coil was lowered. The initial tool had however a slightly too sharp bend on the inner end wire which made it hard to fix it in place during the first few revolutions. It gave a better result than expected, and when the coil was placed on the stator there was almost a 1mm gap between the outer rim of the coil and the stator. The plastic tool was redesign and extended a shallower bend for the inner end was added as well as 0.7 mm of space for an extra set of revolutions. This proved to generate coils with 90 revolutions which should be good enough for the motor and was chosen as the final solution. Two coils placed next to each other on the stator can be viewed in Appendix 6.2.2. However the exact iteration of coil revolutions proved hard to keep, and an error margin of +/-1 revolution needs to be taken into consideration. This should barely be noticeable in the final electric circuit. For exact revolutions see Appendix 6.2.2.

3.5 Connection and marking of the coil wires

Since the mechanical shop wasn't able to mill the stator and rotor before the end date of the project the connection and marking of wires remain untested.

3.6 Distance plates for stator and rotor

The method for the distance plates worked quite well for the large carbon fibre plate fixing the stator. However the 3D-printer was unable to print accurate holes for the drill guide. The holes was well centred, but the diameter did not correspond to the CAD drawing. The drill guide was used none the less, resulting in loss of accuracy. Therefore the drilling of the outer rims was postponed awaiting the rotor mechanics. With the rotor mechanics the accuracy of the drill guide can be validated before the drilling is performed.

3.7 Mechanical appliances

The CAD drawing of the part that locks the ball bearing can be seen in Figure 2, part 5.

3.8 Experimental board

The CAD file was partly produced and the result can be viewed in appendix 6.4. The experimental board remain unfinished due to the time frame.

4 Conclusion and future outlook

The winding process with the 3D-printed plastic tool was a success, and the process of test winding and redesign of the tools saved time in the winding process and allowed for more revolutions in each coil. Printing a winding tool in plastics was an irreplaceable ease in the design process. However when a final design is set, it should be constructed in metal instead, since the plastics are slightly flexible and the accuracy of the winding is reduced.

Regarding the fixation of the coils, the heat transfer adhesive is the best choice if scalability is required. This gives good heat transfer properties and thereby increased cooling. However if the winding process is finalized and there is no need for removing the coils polyester resin should be used instead. It will greatly simplify the winding process, as well as the curing process. If the resin is dripped onto the wire during the winding process about the same heat transfer properties as with the heat transfer adhesive should be achieved.

The desired motor properties as discussed in the introduction are probably achieved with the winding method that has been developed. The heat transfer properties should be as good as possible while some space is left between the coils for air cooling. The power electronics design should probably be developed further and the connection method for the coils should be tested.

5 Acknowledgement

I would like to thank Mauritz Andersson for including me in his work and his persistence at always trying to excel.

I also thank Dana Salar and Johan Abrahamsson for always helping, supporting and advising on any and all challenges, and Frans Rosencrantz and Philip von Heideken for always having the patience to discuss problems, big or small equally.

6 Appendix

6.1 Winding setup

Plastic winding setup:

Metal winding setup:

6.2 Coil revolutions

6.2.1 Aluminium tool

The layer distribution achieved with the first successfully wound coil:
Layer 1: 22 revolutions
Layer 2: 23 revolutions
Layer 3: 22 revolutions
Layer 4: 12 revolutions

Sum: 79 revolutions

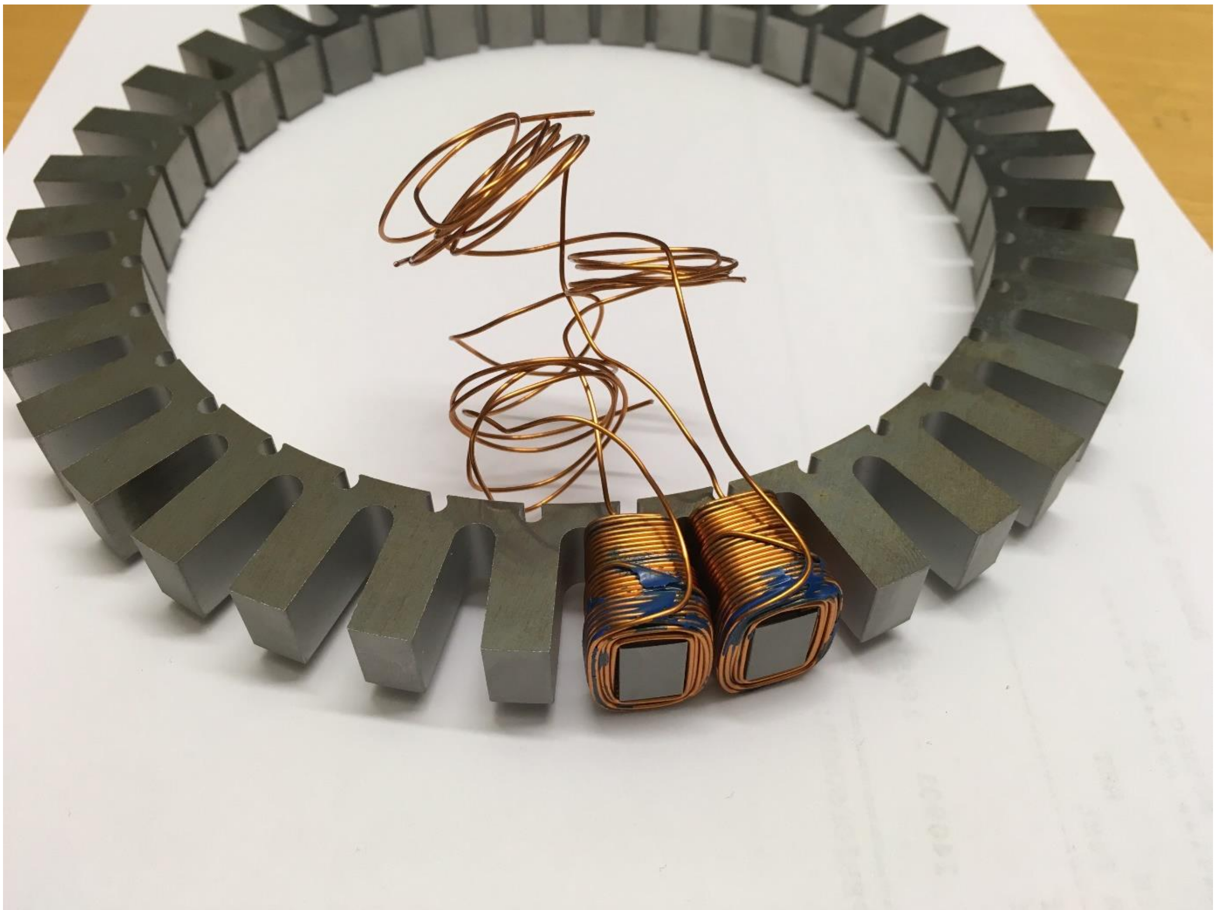
The layer distribution achieved with the final successfully wound coil:
Layer 1: 21 revolutions
Layer 2: 22 revolutions
Layer 3: 21 revolutions
Layer 4: 11 revolutions
Sum: 76 revolutions

6.2.2 Plastic tool

The layer distribution achieved with the first successfully wound coil:
Layer 1: 21 revolutions
Layer 2: 22 revolutions
Layer 3: 22 revolutions
Layer 4: 14 revolutions
Layer 5: 7 revolutions
Sum: 86 revolutions

The layer distribution achieved with the final successfully wound coil:
Layer 1: 22 revolutions
Layer 2: 23 revolutions
Layer 3: 24 revolutions
Layer 4: 15 revolutions
Layer 5: 6 revolutions
Sum: 90 revolutions

Two coils placed next to each other on the stator:



6.3 Fixation method for the coils

Product	Result and comments	Usable?
2-component epoxy	Sufficient adhesion, insufficient temperature properties	No
Delo –ML 5327 1K-Methacrylat	Insufficient adhesion	No
ZAP Z-71 thread locker, permanent	Insufficient adhesion	No
Loctite Super glue	Insufficient adhesion	No
2-component heat transfer adhesive, WLK 5, Fischer Electronics	Sufficient adhesion, good heat properties, expensive	Yes
Polyester resin ULTIMEG 2000/520	Good adhesion, good heat properties, cheap, need heat curing, might deform during heat curing if not fitted to the stator	Yes

6.4 EAGLE circuit