

WIRE-WOUND WINDING

I.1 Type of winding

The maximal thickness of each subassembly of the armature winding is 2 [mm]. Therefore, for construction reasons, it is decided not to use wave winding. Indeed, it would require to wind on both sides of a support, like the core of the PCB and this support should be very thin and rigid at the same time. Indeed, the axial restoring forces being exerted on the wires constituting the coils, the latter have to be rigid enough in order to avoid deformations. Moreover, it allows to test both types of winding as the wire-wound version will then be a lap winding. For the same reasons, it is decided to construct non-overlapping winding.

I.2 Lap windings

There exists many possible shapes to conceive lap windings. However, as it is wire-wound, the simpler the better. Indeed, it is very difficult to produce complex shapes as the wire cannot be bent easily and the final shape of the coils will be quite narrow.

As for the PCB version, the armature winding must have six pole pairs ($p = 6$) and three evenly distributed phases ($N = 3$). The inner radius R_i is still 25 [mm] but the outer radius R_e is enlarged to reach 55 [mm]. This allows to increase the flux linked by the winding. It is possible in this case as there is no need to keep much space around the winding to position the terminals. Furthermore, regardless of the shape of the lap winding, as all the coils are identical and have an axis of symmetry, only the half, located in the first quadrant, of the first coil will be described.

I.2.1 Parallel winding with integral pitch

The first shape that is considered is the parallel winding with integral pitch. Integral pitch means that the pitch of a coil of the armature winding is identical to the pitch of one pole of the PMs arrangement, namely π/p . In the particular case of the test bench, it is equal to 30° . As can be seen in Fig. I.1, the external edge of the active segments of each coil is radial. By contrast, the internal edge of the active segments are not radial but parallel to the external one. Defining w as the width of wires of each coil, the internal edges are spaced of the external ones by this constant distance w . Hence, the colored surfaces correspond to the places occupied by the wire. Fig. I.2a shows a complete phase with its six coils.

The parallel winding with integral pitch can be described, in cartesian coordinates, through the four red points in Fig. I.1. The two first points are already known and given by:

$$\begin{aligned} \{x_1; y_1\} &= \{R_i \cos(\pi/2p); R_i \sin(\pi/2p)\} \\ \{x_2; y_2\} &= \{R_e \cos(\pi/2p); R_e \sin(\pi/2p)\} \end{aligned} \tag{I.1}$$

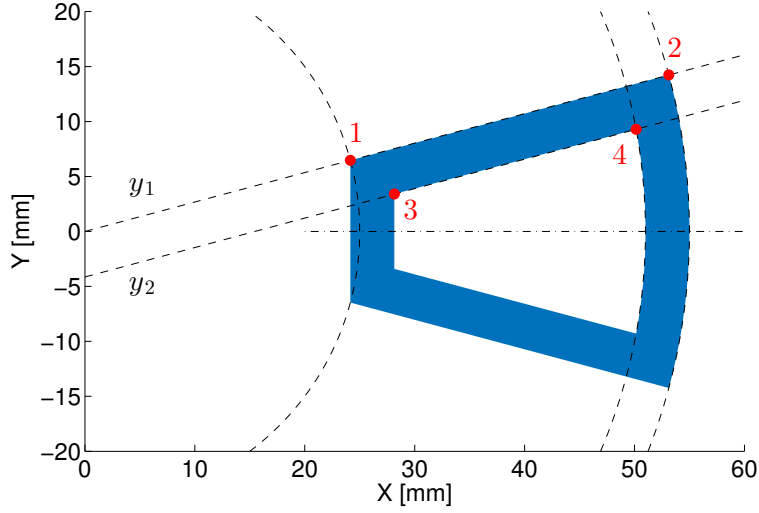


Fig. I.1: Parallel winding: points determination.

The slope m and the intercept p_1 of the straight line y_1 passing through these two points can be easily calculated. Besides, knowing that the difference between the intercepts of two parallel straight lines of slope m and spaced by a distance w is $w\sqrt{m^2 + 1}$, the intercept p_2 of the straight line y_2 is:

$$p_2 = p_1 - w\sqrt{m^2 + 1}. \quad (\text{I.2})$$

As the third point belongs to the straight line y_2 , its coordinates are yielded by:

$$\begin{cases} x_3 = x_1 + w \\ y_3 = mx_3 + p_2 \end{cases} \quad (\text{I.3})$$

The fourth point corresponds to the intersection between the straight line y_2 and the circle of radius $R_e - w$ centered in $\{0; 0\}$:

$$\begin{cases} mx_4 + p_2 = y_4 \\ (R_e - w)^2 = x_4^2 + y_4^2 \end{cases} \quad (\text{I.4})$$

Solving for x_4 and y_4 gives:

$$\begin{cases} x_4 = \frac{-mp_2 + \sqrt{(R_e - w)^2(m^2 + 1) - p_2^2}}{(m^2 + 1)} \\ y_4 = mx_4 + p_2 \end{cases} \quad (\text{I.5})$$

It will not have escaped the careful reader that the wire follows a straight line in the bottom of each coil: it is much easier to wind around a convex form. Besides, the different coils have to be connected in series, but this will be discussed later. However, as can be seen in Fig. I.2b, it is not possible to place the three phases in the same plane without conflict between them and, for construction reasons, the winding has to be non-overlapping, as stated in section I.1.

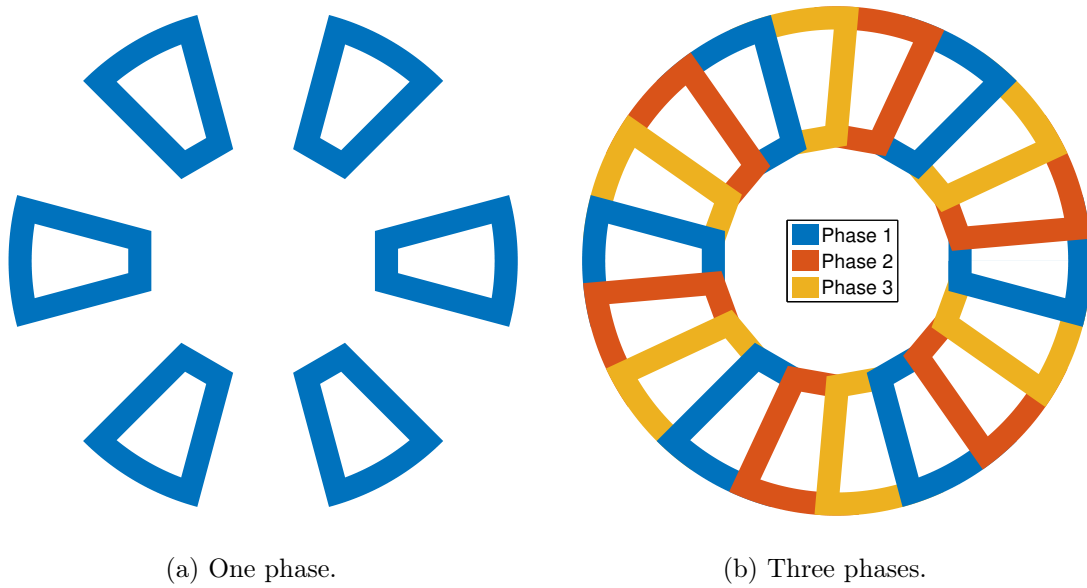


Fig. I.2: Parallel winding with integral pitch.

I.2.2 Parallel winding with fractional pitch

The parallel winding offers the major advantage to be constituted of the longest radial active segments. Therefore, whilst keeping this shape, the easiest way to obtain non-overlapping winding with three phases is to reduce the pitch, yielding a fractional pitch. Obviously, the emplacement of the center of each coil of a phase remains identical.

Version A

As there are N phases, the fractional pitch is given by the angular opening of a pole pair pitch divided by N , yielding $2\pi/pN$. The parallel winding with fractional pitch can be described through four points defined in the same way as for the integral pitch. The two first ones are then given by:

$$\begin{aligned} \{x_1; y_1\} &= \{R_i \cos(\pi/pN); R_i \sin(\pi/pN)\} \\ \{x_2; y_2\} &= \{R_e \cos(\pi/pN); R_e \sin(\pi/pN)\} \end{aligned} \quad (\text{I.6})$$

Following the same reasoning as for the integral pitch, the two last points can be determined using the expressions (I.2), (I.3) and (I.5). In the particular case of the test bench, the fractional pitch and then each coil of the winding covers 20° . The resulting winding composed of one phase is shown in Fig. I.3a. Compared with the integral pitch, the different coils become very narrow and the flux linked is obviously lower. Fig. I.3b shows a complete subassembly of the armature winding constituted of three phases.

Version B

For construction reasons, it can be interesting to reduce again the pitch of each coil so that the neighbouring coils do not directly adjoin, as shown in Fig. I.4. The minimal distance d_p between two consecutive coils, which then belong to different phases, is arbitrarily set to 1 [mm]. This parallel winding with fractional pitch can be anew described through four points. Fig. I.5 shows the two first consecutive coils. The red point represents the point

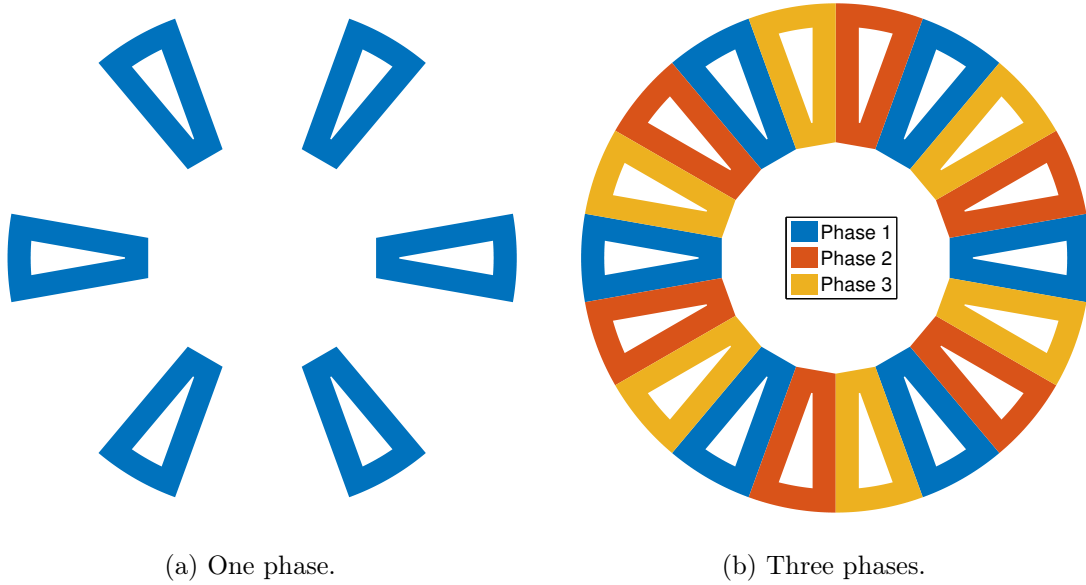


Fig. I.3: Parallel winding with fractional pitch version A.

$\{x_1; y_1\}$ of the version A. Hence, compared with version A, the pitch is reduced by 2ν , with $\nu = \sin^{-1}(d_p/2R_i)$. The two first points of the version B are then given by:

$$\begin{aligned} \{x_1; y_1\} &= \{R_i \cos(\pi/pN - \nu); R_i \sin(\pi/pN - \nu)\} \\ \{x_2; y_2\} &= \{R_e \cos(\pi/pN - \nu); R_e \sin(\pi/pN - \nu)\} \end{aligned} \quad (\text{I.7})$$

Again, the two other points can be determined using the expressions (I.2), (I.3) and (I.5). This version offers two main advantages. On the one hand, if one coil has not exactly the right shape, it does not impact the neighbouring ones as they are separated. On the other hand, the free space between the coils can be occupied by the support, allowing to rigidify the complete winding. However, it also suffers from several drawbacks. Obviously, the flux linked by the winding is a little bit smaller as the pitch is shorter. Besides, the width w has to be reduced to 4 [mm] instead of 5 [mm] for construction reasons. Finally, the value of the distance d_p results from a trade-off between the rigidity of the support and the flux that is not linked as the pitch is reduced.

1.3 Support

As both versions A and B of the parallel winding with fractional pitch have their advantages and drawbacks, they are both analysed hereinafter. Regardless of the version, the winding has to be fixed on a support which must have at least six screw holes spaced by 60° so that it can be attached to the stator. The inner and outer radii of the support are 22.5 and 68 [mm], respectively, and the clamping radius is 62 [mm].

1.3.1 Version A

The version A is constituted of 18 coils that each occupies 20° . All the coils are wound separately and then assembled so as to form a ring, as shown in Fig. I.3b. It would be extremely difficult to glue the different coils together and then to glue this assembly to the support. Therefore, an alternative is to pour a resin in a cast containing the support and

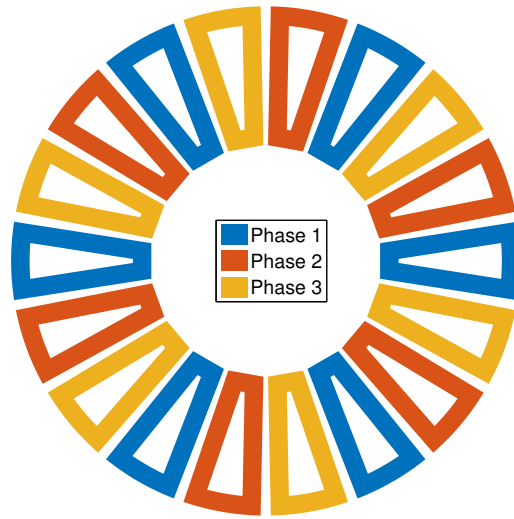


Fig. I.4: Parallel winding with fractional pitch version B: three phases.

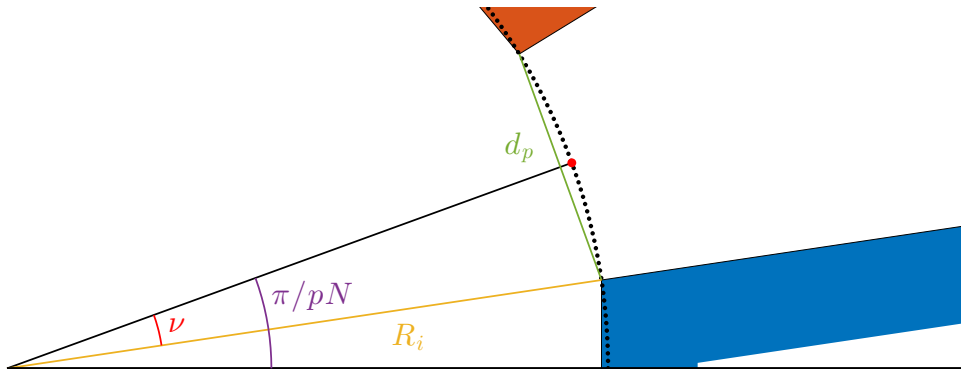
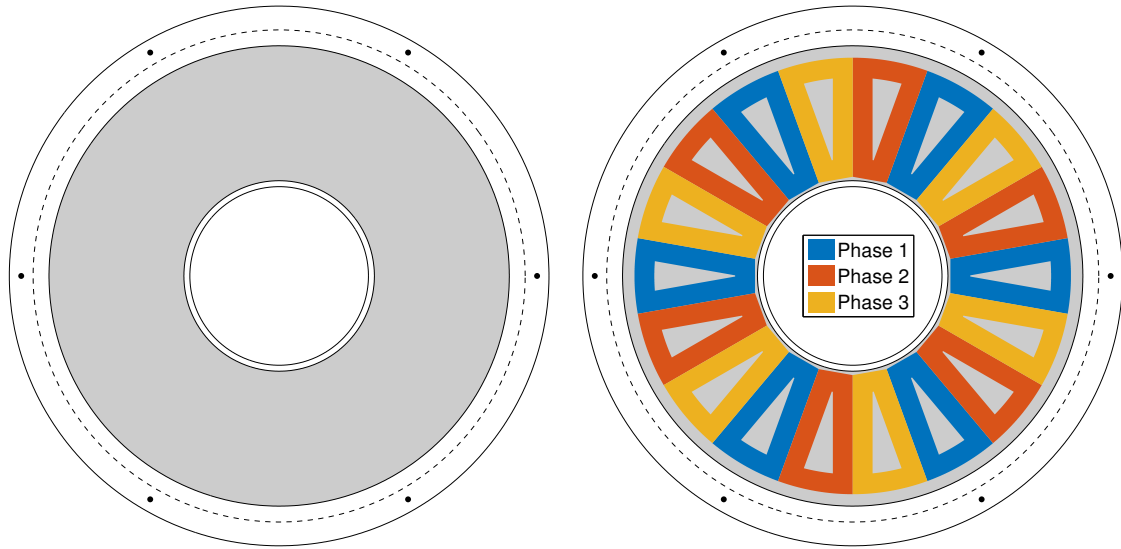


Fig. I.5: Parallel winding with fractional pitch version B: points determination.

the windings. Fig. I.6a shows the proposed support. The external limits are represented by the solid lines and the clamping diameter by the dashed line. The larger inner and smaller outer radii are respectively 24 and 58 [mm]. Finally, placing the support on a non-adherent material, the grey zone is equivalent to a cast and is then filled with the resin after the phase windings are correctly positioned, as shown in Fig. I.6b.

I.3.2 Version B

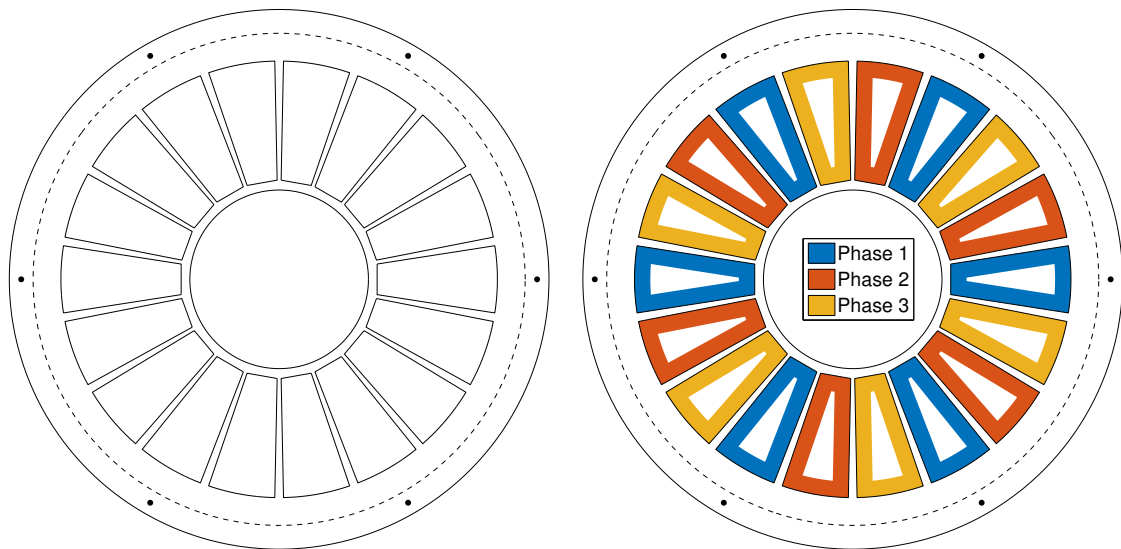
The parallel winding version B is constituted of 18 coils that are all mechanically separated. However, it should be recalled that the coils of the same phase are connected in series in order to avoid the effect of the eccentricity at second order (see section 3.3.2). Furthermore, as mentioned earlier, the space between consecutive coils is occupied by the support to rigidify the complete winding. The resulting support is shown in Fig. I.7a. Finally, in order to fix the coils to the stator, their external wires are glued to the support, as can be seen in Fig. I.7b.



(a) Without the phase windings.

(b) With the phase windings.

Fig. I.6: Support for the lap winding version A. External limits (solid lines), clamping diameter (dashed line) and cast for the resin (grey zone).



(a) Without the phase windings.

(b) With the phase windings.

Fig. I.7: Support for the lap winding version B. External limits (solid lines) and clamping diameter (dashed line).

I.4 Windings fabrication

Regardless of the version chosen for the lap winding (A or B), the coils are wound in the same way. To this end, a support is prototyped with 3D printing. As shown in Fig. I.8a, it is composed of two parts, the bottom and the top. When the bottom is inserted into the top, the vertical space between them is exactly 2 [mm] and this space has to be fully filled with wire. Fig. I.8b shows the support closed and the wire wound around the extruded

part of the bottom. The wire has been glued all along the operation while the support was pressed. The top part of the support is then removed, as shown in Fig. I.8c and glue can anew be added. Finally, the bottom part is also removed, allowing to obtain the coil, as shown in Fig. I.8d. However, this method does not give perfect result and has to be improved. The resulting coil can then, for example, be glued into the support for the version B, as shown in Fig. I.9.

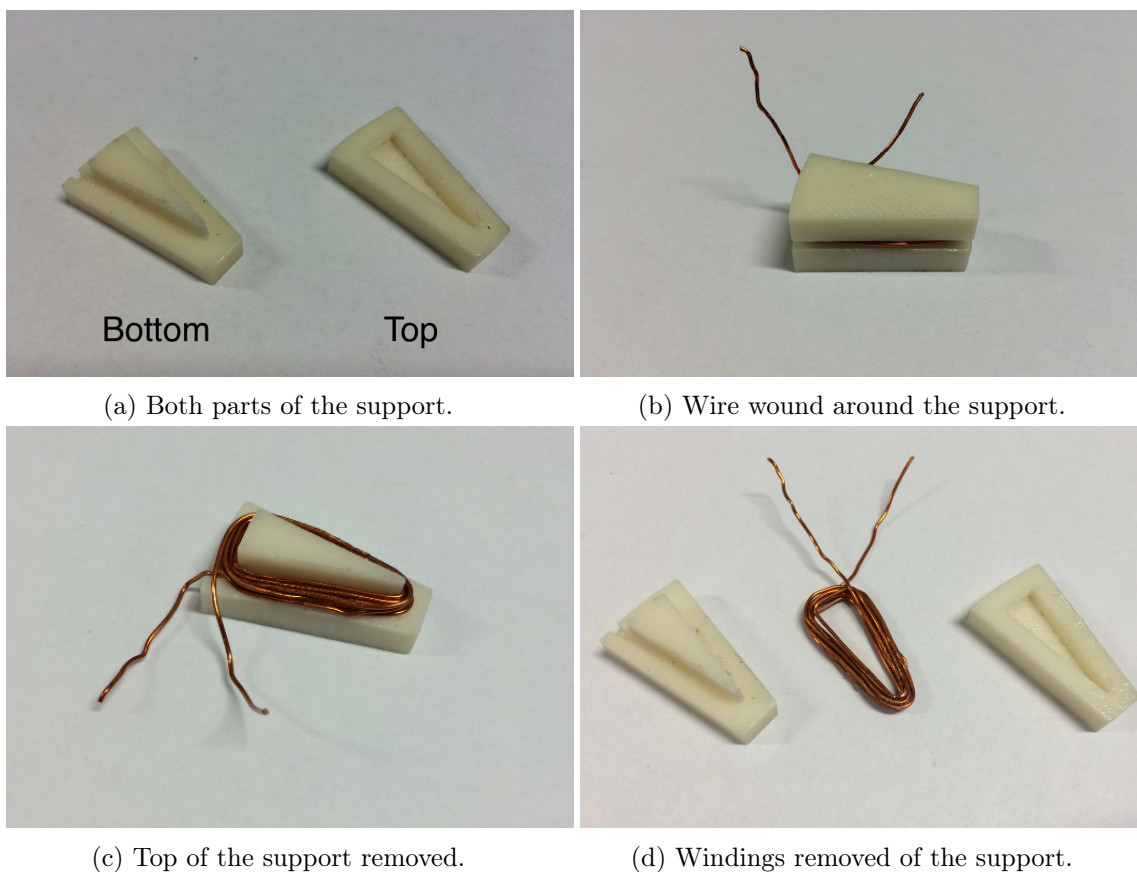


Fig. I.8: Wire-wound windings fabrication.

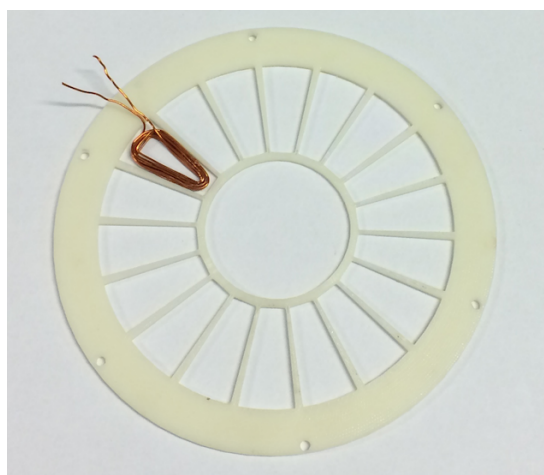


Fig. I.9: Wire-wound winding placed in the support, version B.