



INDIRES
Information Driven Incident Response

User Manual Drilling Rig Design

29th December 2020

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1 INTENDED AUDIENCE

An output of the INDIRES project is user documentation for each of the products produced during the project. However, the status of the various products differs and, for this reason, the intended audience for the *User Documentation* will be different for each product. It is necessary, therefore, to indicate the type of user who will benefit from this particular *User Document*.

Withing the INDIRES project, we have developed a new drilling rig concept, the mathematical models, and all necessary drawings, ready to be implemented into real devices in a follow-up project. This document is intended for institutions who would like to cooperate in the construction of a prototype and performance testing of the speech method of rock drilling.

In the traditional drilling process the rock's natural frequencies usually do not occur and in special situations this process is quite often long and sometimes dangerous. But if we can determine the type of rock or substrate materials and thus determine the natural frequency of these materials, we can generate the frequency equal or near to the natural frequency and in consequence we can drill holes in a shorter time than in the traditional methods. In that way the idea of a novel method of drilling by using a torsional torque generator in a drilling process was born. Within the scope of INDIRES, its perceived application is for drilling emergency rescue tunnels. Here, the reduced size and weight of the rig make it much more possible for rescue teams to transport it to the area in which it's required.

The designed drilling rig consists of five main components: the main driving motor (MDM), the induction torque converter (ITC), the electromagnetic torsional vibration generator (TVG), the internal screw conveyor (ISC), and the cutting / drilling head (DH). This document is divided into five parts showing and describing the design which has been prepared for all main components of drilling rig.

This *User Document* is intended for readers from institutions who want to undertake further cooperation, in the form of a joint grant, aimed at the construction of the first prototype and conducting drilling tests. In addition, it is important to prepare an appropriate control algorithm for the entire drilling rig.

Developers who want to know more, and perhaps to discuss possible collaborative opportunities, are referred to *Section 8*.

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2 OVERALL DESIGN OF DRILLING RIG

The new drilling rig consists of five main components: an electromagnetic torsional vibration generator, a torque converter, a drive motor as well as an internal screw conveyor and drilling / cutting head. *Figure 1* shows a cross-section through the entire drilling rig, where (1) denotes the torsional vibration generator (TVG), (2) the induction torque converter (ITC), (3) the main drive motor (MDM), (4) the cutting / drilling head (DH) and (5) the internal screw conveyor (ISC). The drilling rig system can be divided according to the operating speed of its components, which are categorized as high-speed and variable-speed areas. The main drive motor MDM works in high-speed area – it generates the main drive torque for the drilling / cutting head DH and, at the same time, it drives the internal screw conveyor ISC. The induction torque converter ITC operates between the high-speed and variable-speed areas, and is responsible for the non-contact transfer of the drive torque for the torsional vibration generator TVG and the drilling / cutting head DH.

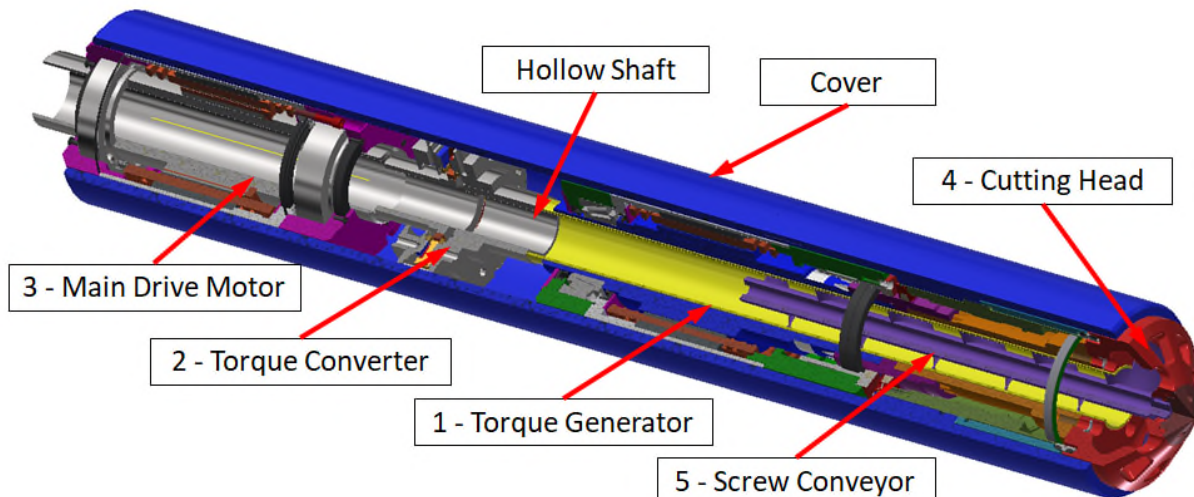


Figure 1 – Drilling rig cross section. View on internal components

The drilling rig system can be divided taking into consideration the operating speed of its components, specifically the high-speed and variable-speed areas. The main drive motor (MDM) works in the high-speed area – it generates the main drive torque for the drilling / cutting head and at the same time it drives the internal screw conveyor. The induction torque converter (ITC) operates between the high-speed and variable-speed areas, and is responsible for the non-contact transfer of the drive torque for the torsional vibration generator (TVG) and cutting head. In the variable-speed area is the torsional vibration generator (TVG) coupled with the cutting head.

The torque flow diagram for the whole drilling rig is presented in *Figure 2* (Trawinski *et al.*, 2019; 2020). The main driving motor (MDM) delivers the fundamental driving torque, denoted by in *Figure 2* by T_{eM} , for the indirect drive of the drilling / cutting head (DH) by the torque component T_{eC} , and the direct drive of the internal screw conveyor (ITC) by the torque component T_{eS} . The internal screw conveyor (ITC) is responsible for the transfer of the mined rock from the drilling / cutting head (DH)

across the whole drilling rig, through the internal channel – all the drilling rig components are made as a hollow shaft. The internal conveyor rotates with the same speed as the main driving motor (MDM). The torque component T_{ec} , which is an input torque for the induction torque converter (ITC), is transferred by ITC, but the output torque T_{ed1} is lower than T_{ec} because a part of torque T_{ev1} is consumed for the ventilation and cooling system of ITC. The output torque T_{ed1} of ITC becomes the input torque for the electromagnetic torsional vibration generator (TVG).

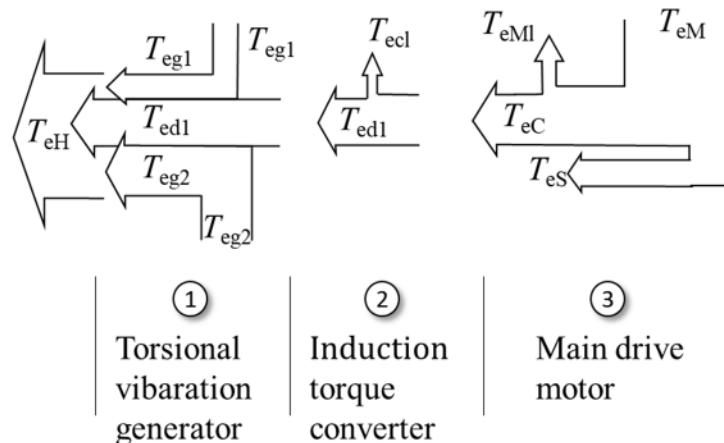


Figure 2 – Torque Flow in Drilling Rig (Trawinski et al, 2019; 2020)

TVG produces two additional torque components: T_{eg1} and T_{eg2} . The first one is a residual torque with asynchronous nature (not alternating) – it helps drive the drilling / cutting head DH in a desired direction. But the other one (T_{eg2}) is an alternating torque which forces the drilling / cutting head DH to torsional vibration, perpendicular to the rock surface. Finally, the torque T_{eH} exerted on the drilling / cutting head DH consists of three components, two of a continuous nature T_{ed1} and T_{eg1} , and one alternating T_{eg2} . Such composition of torques gives a very wide range of possibilities to control the drilling process. It ensures, independently of the driving torque T_{ed1} , settings of amplitudes and frequencies of the alternating torque T_{eg2} . Even when the drilling / cutting head DH is locked, after transporting the mined material by the internal screw conveyor ITC, all the T_{eM} torque may be transferred by the ITC to the drilling / cutting head DH. The main driving motor (MDM) will never be locked, because the ITC transfers the torque in a contactless manner. That gives a chance to unlock the cutting head by changing frequencies and amplitudes of the alternating torque T_{ed2} generated by the TVG. Locked drilling / cutting head DH states during a drilling process may happen very often and all the drilling rig components may affect a strong current and thermal load.

3 TORSIONAL TORQUE CONVERTER DESIGN

The torsional vibration generator TVG is an electromagnetic energy converter which transforms electrical input energy into output energy of mechanical vibration. In this case the vibrations occur as a result of mutual interactions between high order magnetic field harmonics in the air gap of the TVG, which produce a torsional electromagnetic torque and finally torsional vibration of the shaft.

The input electric energy is converted into a rotating magnetic field thanks to the stator windings. The construction of the stator windings and their space distribution form the amount of magnetic field harmonics and we call them excitation space harmonics. The induced currents in the rotor squirrel cage of the TVG produce the reflected magnetic space fields harmonics. The magnetic field space harmonics excited by stator windings interact in the air gap with magnetic field space harmonics reflected by the rotor. However only the chosen magnetic field space harmonics generate the electromagnetic torsional torque. The mechanism of generation of torsional torque is described in detail in (Trawinski *et al.*, 2020).

Figure 3 shows the cross section through the whole designed torsional vibration generator TVG. The main components of the torsional vibration generator are: the stator frame, the stator yoke (composed with stack of laminated iron plats), the 3-phase stator winding, the rotor cage, the hollow shaft, the inclined bearing, the plain bearing and the covers of the bearings.

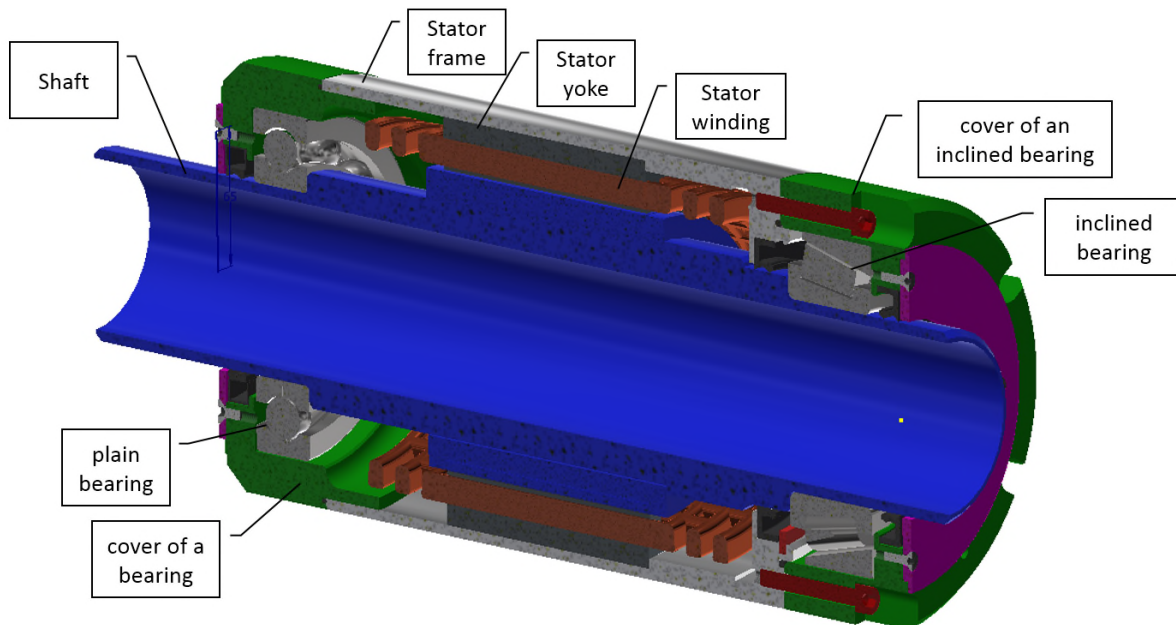


Figure 3 – The General View of Designed Torsional Torque Generator [D4.1 – Report on Drilling Rig: Field Calculation]

All detailed drawings of all components of torsional vibration generator are included in *Appendix A*.

3.1 3-phase Stator Winding and Stator Drawings

The stator winding of the torsional torque generator TVG are designed as a single-layer disposed in the slots 36 extending symmetrically ($Q_s=36$). Each phase consists of two coil groups with different turn spans equal to 7, 9 and 11 slots, and form a 2-pole magnetic field. The winding diagram is shown in *Figure 4*.

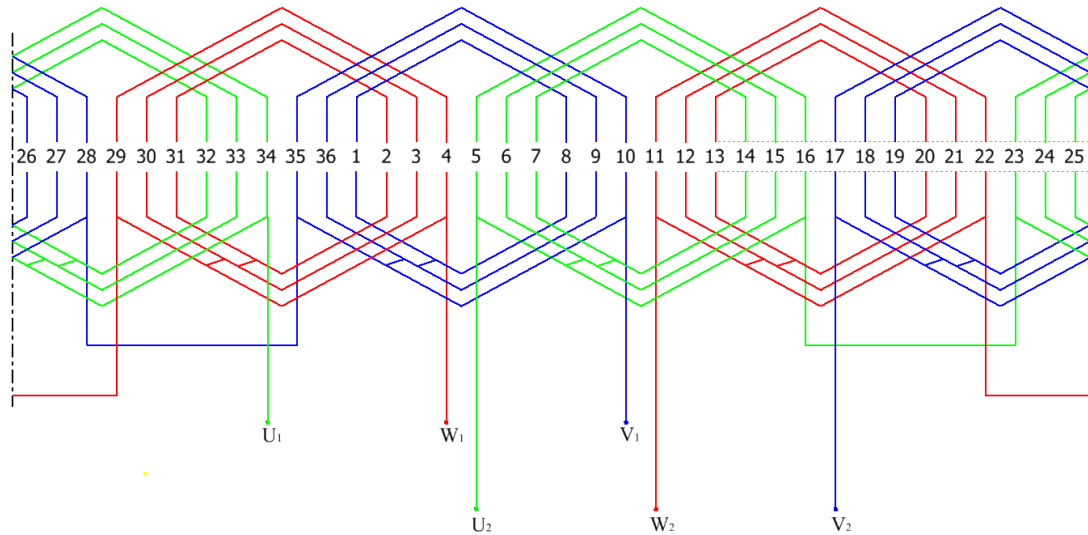


Figure 4 – Diagram of Winding

Winding data of the stator winding is shown in *Table 1*.

Rated voltage	$U_n[V] \Delta/Y$	230/400
Rated frequency	$f_n [Hz]$	50
Number of poles	$2p$	4
Span of the turn		7,9,11
The number of coils in series per phase	N_s	252
The number of turns in coil	N_t	42
The number of coils connected in series	N_q	2
The number of parallel branches	N_f	1
Diameter of the winding wire	$d_w[mm]$	0,8
The number of parallel wires in the coil	N_p	2
Phase resistance at 20 °C	$R_{s20}[\Omega]$	2,48
Assay voltage	$U_{test}[V]$	2100
The length of the stator package	$l_{Fe}[mm]$	114

Table 1 – Winding Card of Generator and PMSM Motor

Each side of the coil occupies the stator slots symmetrically distributed around the internal surface of the stator lamination stack – stator yoke. The shape of stator slot is presented in *Figure 5*.

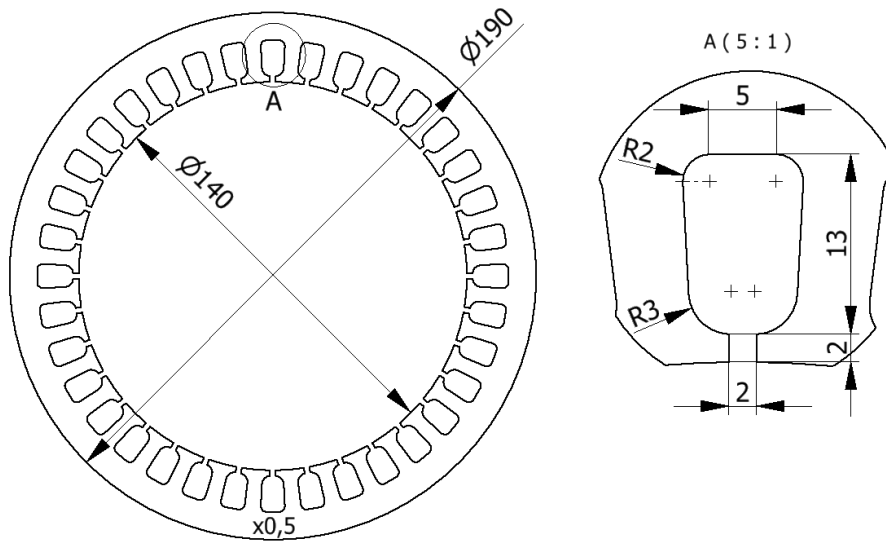


Figure 5 – Dimensions of a Stator Sheet and Stator Slots

3.2 28-phase Rotor Cage and Rotor Drawings

The rotor of the torsional torque converters consist of the following components: the copper rotor bars with copper bars end rings, the rotor laminated iron stack (rotor sheets of rotor yoke), and the hollow shaft. In *Figure 6* the general isometric view of torsional generator rotor design is shown.

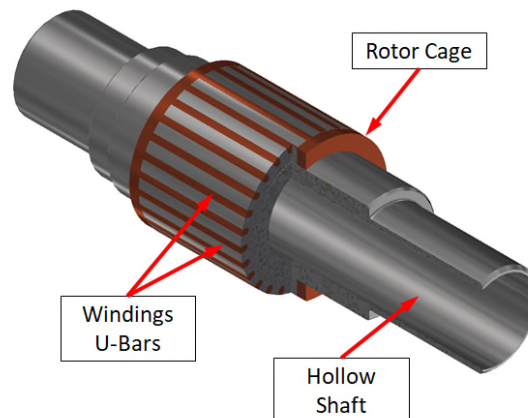


Figure 6 – View of Cross-section of Rotor of Torsional Torque Generator

Detailed drawings of rotor single iron plates are shown in *Figure 7*, also in this same figure is shown the shape of the rotor slots for the rotor bars. The rotor slots are symmetrically distributed around the external circumference of the rotor sheet.

In *Figure 8* the cross section and drawing with dimensions of the shaft is shown.

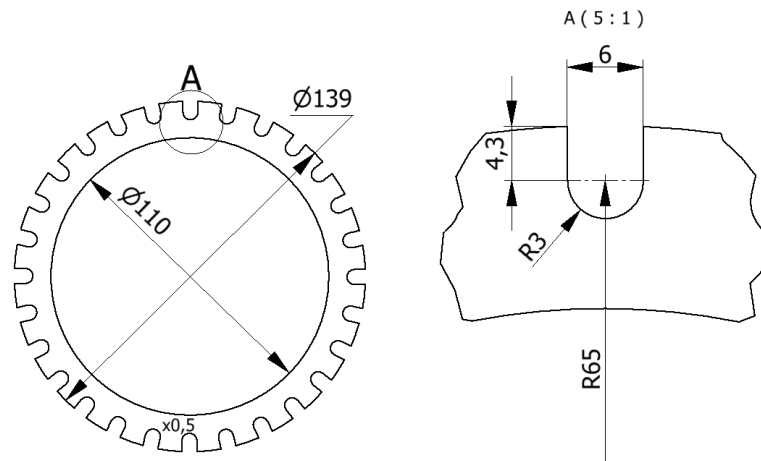


Figure 7 – Rotor Sheet & Rotor Slots of Torsional Torque Generator

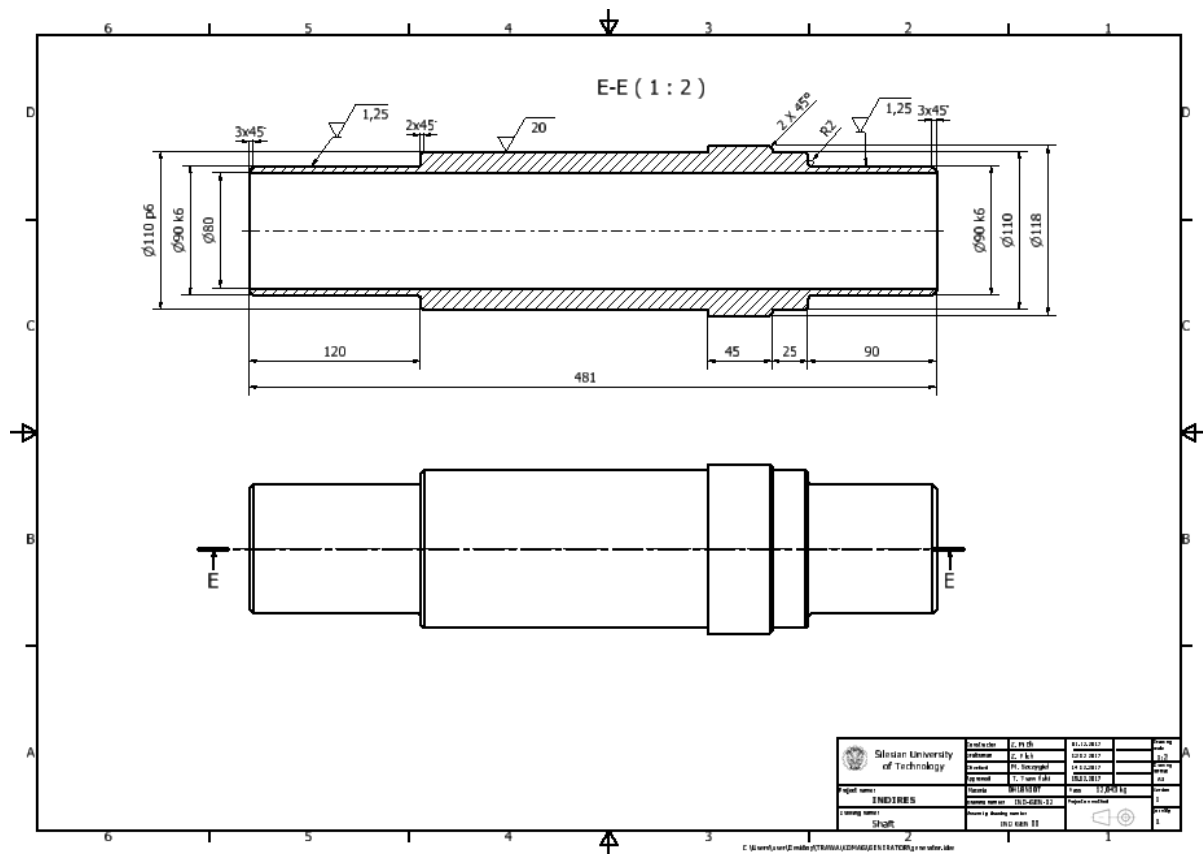


Figure 8 – Cross Section of Shaft

3.3 Bearing System of Torsional Vibration Generator

The following bearings were chosen: SKF QJ 218 N2MA and BS 3134 SKF T2ED.

4 INDUCTION TORQUE CONVERTER DESIGN

An important element, separating the torsional vibration generator and the main drive motor mechanically but coupling them electromagnetically, is the induction torque converter. The induction torque converter is an electro-mechanical device which converts mechanical energy into mechanical energy (with constant transmitted power but different angular rotation speed and different torque). This is achieved by electro-magnetic fields excited by a set of permanent magnets, which interact with the electromagnetic field excited by the current induced (as a result of permanent magnets rotation) in the windings. The input mechanical energy is delivered from the driving motor. The generated motion is assumed to be rotating motion, and this generates a rotating electromagnetic field – the mechanical energy (of rotating masses) is transformed into the energy stored in rotating magnetic fields. These rotating magnetic fields excite the current flow in the windings of the induction torque converter, and finally excite the magnetic fields which interact with the rotating magnetic fields. This interaction forces the windings sets to move – the energy stored in the magnetic fields is transformed into mechanical energy (of windings motion) again. *Figure 9* shows the elements of the torque converter: the excitation system (1), the receiving element (2), the driven shaft (3), the output shaft (4), permanent magnets (5), and windings (6). The torque converter shown in the figure can be extended with additional disks, thanks to which it is possible to increase the values of the transmitted powers and torques. This type of solution allows the converter to be scaled depending on the needs.

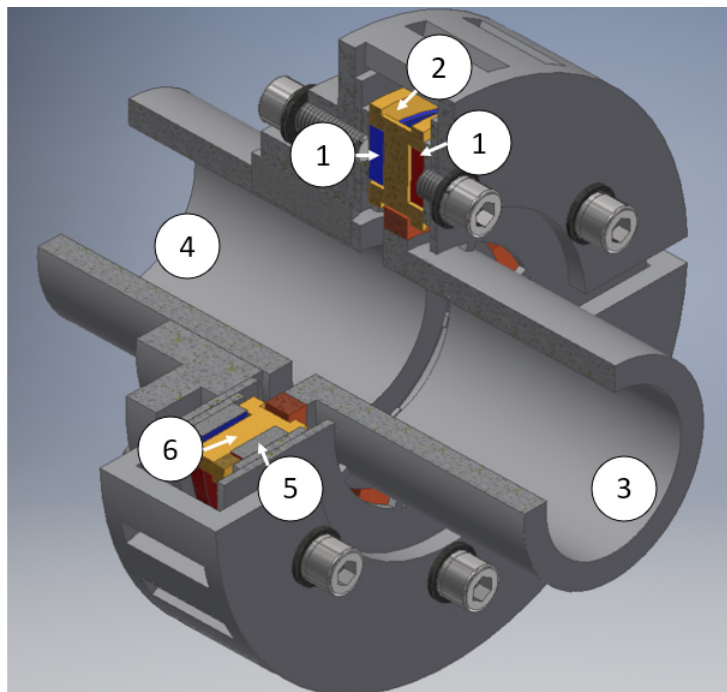


Figure 9 – Cross Section of Shaft

Figure 3 shows the cross section through the whole designed induction torque converter.

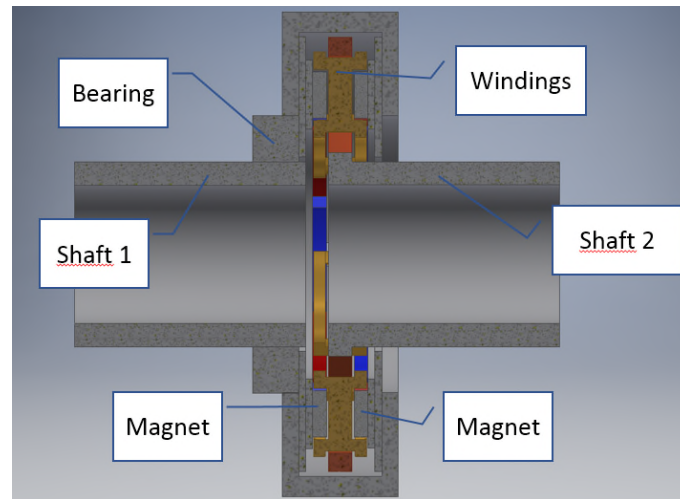


Figure 10 – General View of Cross-section of Induction Torque Converter

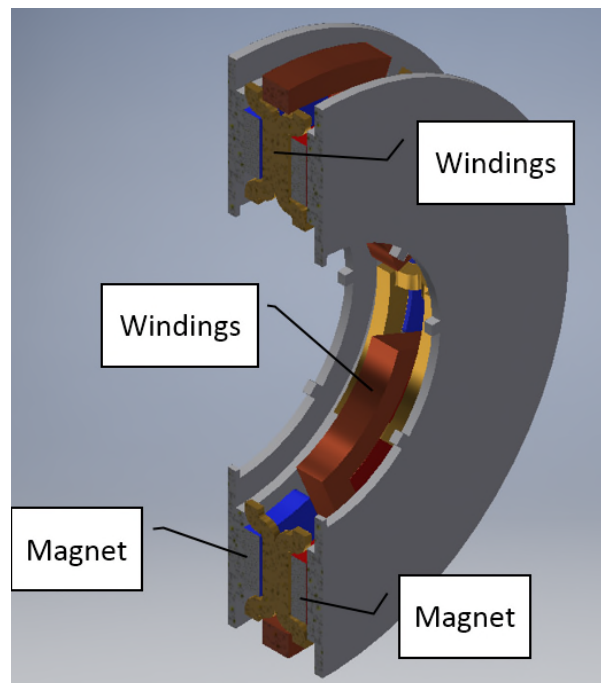


Figure 11 – Cross-section through Rotor and Stator disks

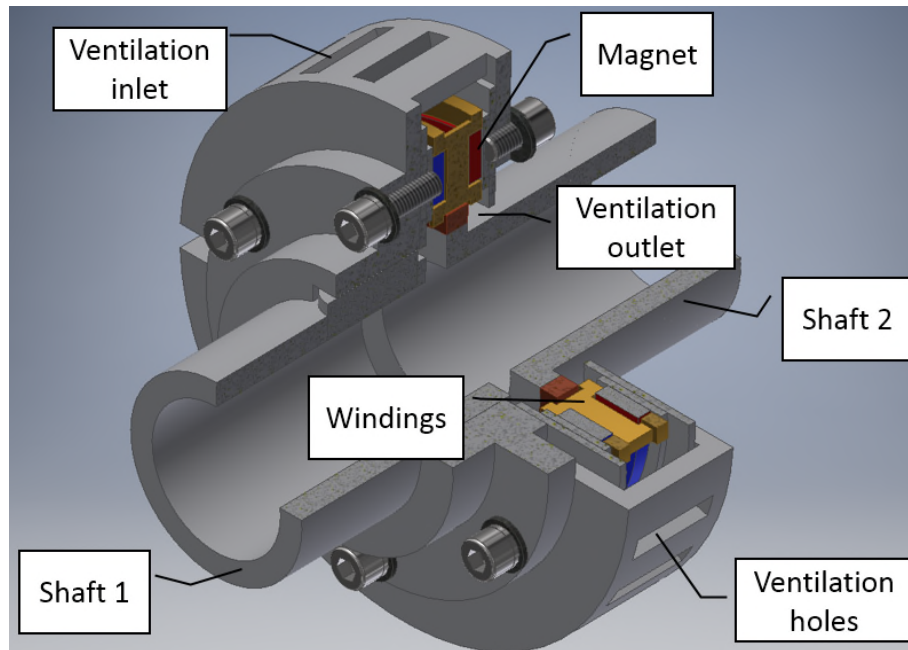


Figure 12 – Cross-section across Induction Torque Converter and its Ventilation System

The sleeve is mounted on the shaft 1, to which it is connected using the keyway A22x14. The shaft 1 is connected to the transmission shaft. A steel disc with a shoulder (spacer ring) is fixed to the sleeve by means of screws. 8 magnets are glued on the shoulder, so that their poles are arranged alternately towards the cage's, N / S / N / S poles. A closure is attached to the disc, which consists of two halves of the cylinder, hollow inside. The closure has ventilation openings around the perimeter, facilitating cooling of the winding. A second disc with a shoulder (distance ring) and magnets facing the disc magnets of the first opposite pole is attached to the closure, according to the N-S, S-N key. The closure is supported by a bearing 2Z6015-2Z, which is embedded in the bearing seat and on shaft 2, connected to the receiving shaft. The winding cages are also fixed on shaft 2. The cages are filled with resin. The components of the converter are made of non-magnetic steel X40MnCr18.

All detailed drawings of all components of induction torque converter are included in *Appendix B*.

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5 MIAN DRIVING MOTOR DESIGN

The third element of the drilling rig is the main drive motor. This motor is designed using permanent magnets and can be classified as a permanent magnet synchronous motor – a kind of electromechanical transducer. In this kind of transducer – in the case of conversion of electrical energy into mechanical energy – electric motors, in which previously magnetized permanent magnets are used, have one uncontrolled source of the magnetic field, related to permanent magnets. The second source of the magnetic field is the winding supplied with electrical energy. The magnetic field generated by the winding can be either a direct field or a time-varying field, where the value of the magnetic field is determined by the parameters of the power supply. In the case of 3-phase AC motors (e.g. synchronous motors), the field generated by the winding is a rotating field with a rotational speed depending on the frequency of the supply source. The interaction of the magnetic field produced by the winding and the magnetic field produced by the magnets is the source of the electromechanical torque (mechanical energy) produced by the motor. This motor generates the necessary driving torque to rotate the cutting head in the desired direction and drive the screw conveyor. The motor windings are made in the same way as the torque generator windings, i.e. they have the same number of pole pairs, the number of phases and they occupy the same number of slots. This approach will significantly reduce the cost of prototyping in the future, as the stators and stator windings are the same in the torsional vibration generator and the main drive motor. *Figure 13* shows the main components of the motor: stator windings, hollow rotor shaft, cover, bearings.

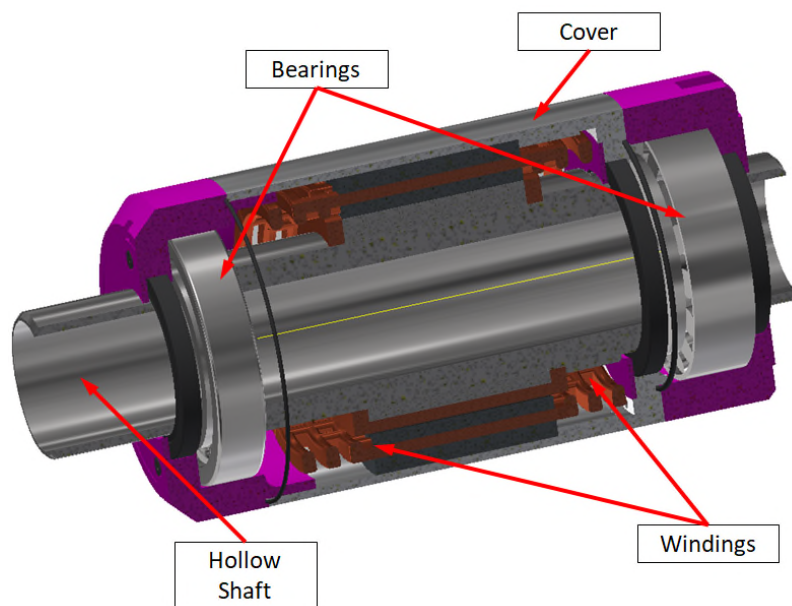


Figure 13 – View of Cross-section of Driving Motor

5.1 Stator and Stator Windings of Main Drive Motor

The stator of the main drive motor consists of a stator laminated sheet with the same number of slots as the torsional vibration generator. *Figure 14* shows the shape of the stator sheet.

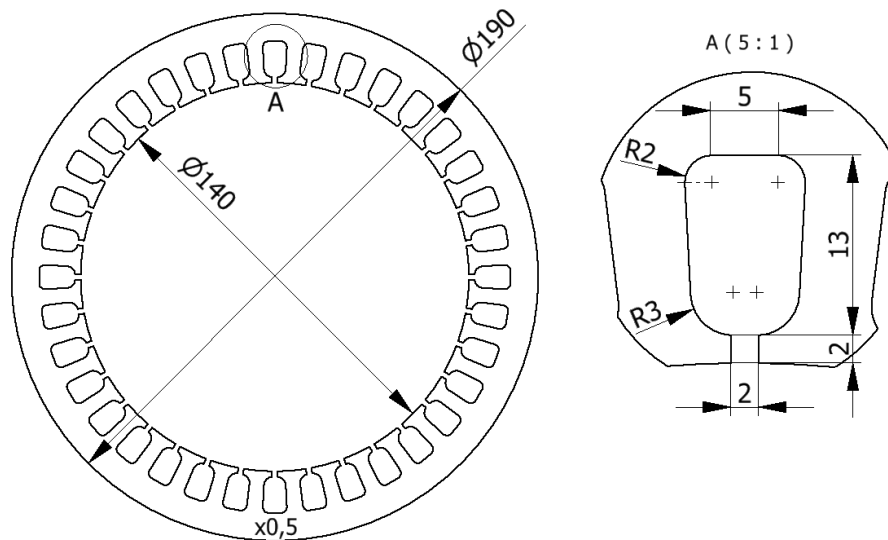


Figure 14 – Dimensions of a Stator Sheet and Stator Slots of Main Drive Motor

The stator winding of the main motor windings is a single-layer disposed in 36 slots extending symmetrically ($Q_s=36$) (winding data of the stator winding is shown in Table 1). The winding diagram is shown in Figure 4

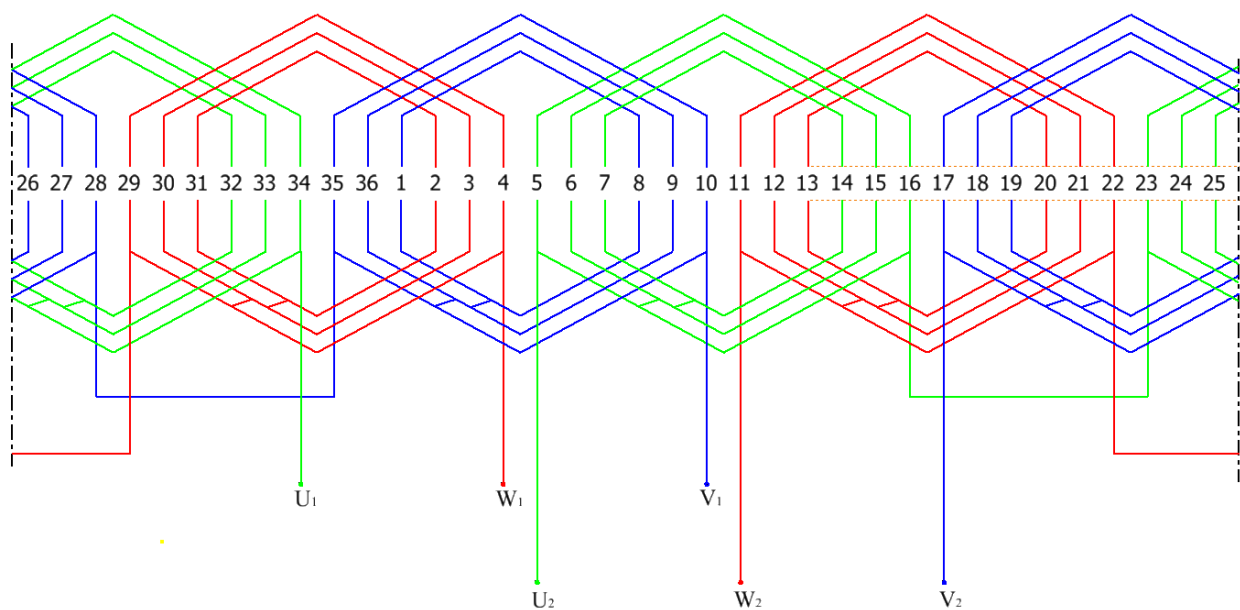


Figure 15 – Diagram of Stator Winding

5.2 Rotor of the Main Drive Motor

The rotor is made of a 0.5mm thick sheet of steel (including insulation). The package sheets are punched on a progressive puncher and made of V 600-50 A DIN 46400 isotropic tape, in insulation I3 applied in the rolling process, with maximum thickness $a_i = 3 \text{ g m}^{-2}$. The minimum induction of the plates at intensity $H = 2500 \text{ A m}^{-1}$ is $B_{2500} = 1.63 \text{ T}$. The magnetization characteristics of the sheet are shown in *Figure 16*.

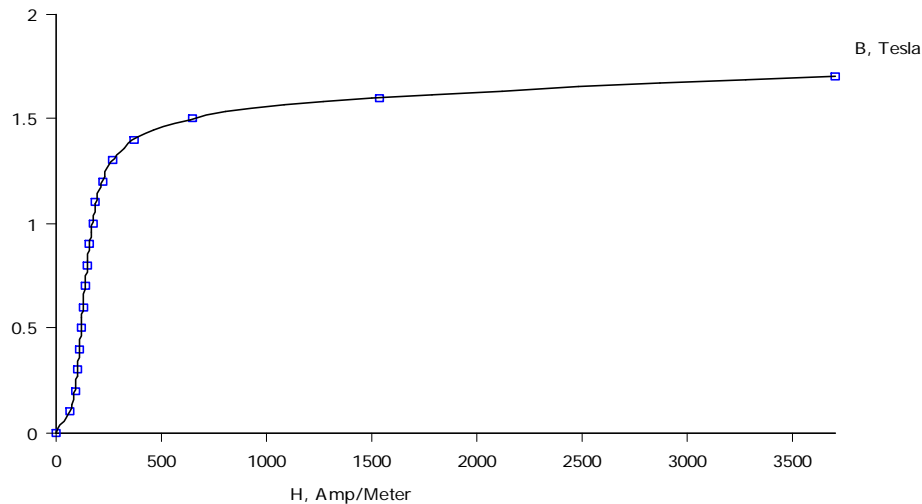


Figure 16 – V 600-50 A DIN 46400 Isotropic Sheet Magnetization Characteristics

A drawing of the rotor with surface permanent magnets is shown in *Figure 17*. N42H permanent magnet has been chosen. The rotor is a cylindrical ferromagnetic core – iron laminated sheets, placed on a hollow shaft. Radially magnetized, permanent arched magnets are glued on the core. In order to eliminate the cogging torque, the magnet was divided into two parts – two cylinders with the length equal halve length of rotor lamination ($l_k = 114$ millimeters), which were shifted in relation to each other by 5° .

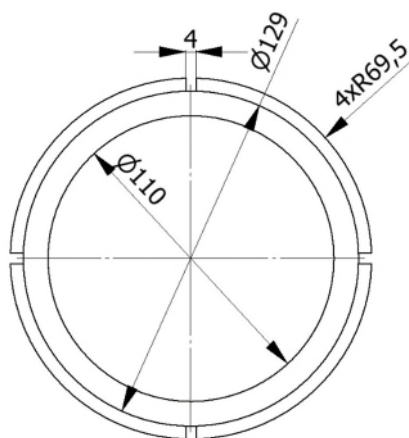


Figure 17 – Rotor with Permanent Magnets

The rotor hollow shaft has the same dimensions as the torsional vibration generator. In *Figure 18* the rotor hollow shaft is shown.

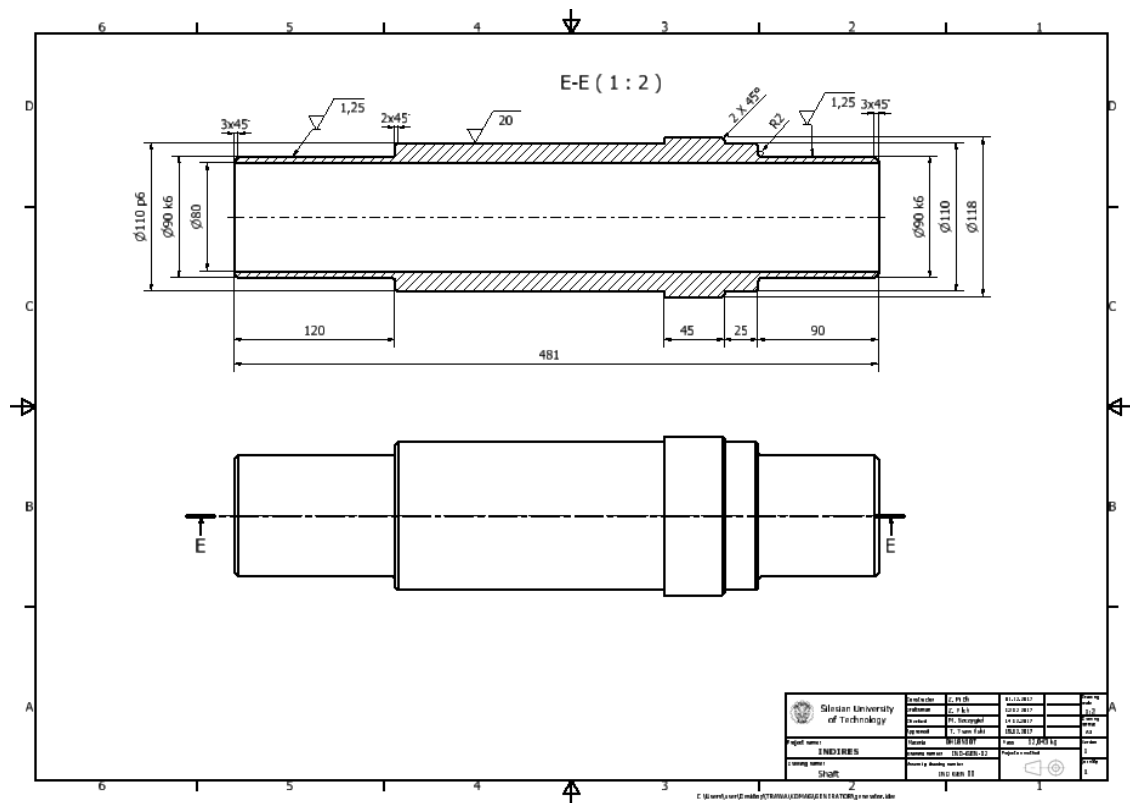


Figure 18 – Cross Section of Shaft of Main Drive Motor

The other elements – the motor housing, bearings, bearings cover etc. – are the same as the torsional vibration generator, but for general purposes the drawings are summarized in *Appendix C*.

6 SCREW CONVEYOR

The designed screw conveyor, shown in *Figure 19*, is inserted into the hollow shafts of all the drilling rig components. The main drive motor drives this screw conveyor, assuring it of the desired high rotation speed and torque.

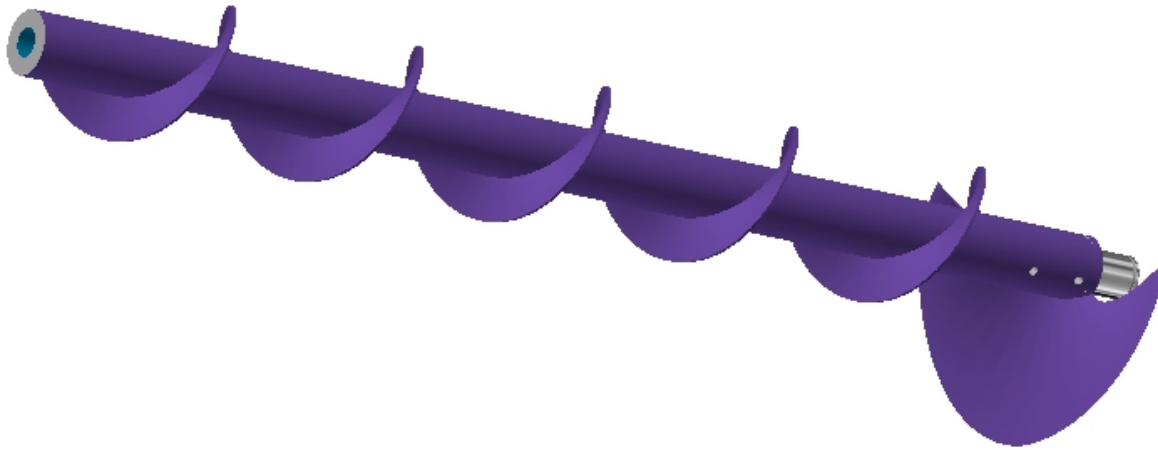


Figure 19 – Cross Section of Shaft of Main Drive Motor

Detailed drawings of the screw conveyor are provided in *Appendix D*.

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7 DRILLING / CUTTING HEAD

The drilling / cutting head consists of the following components: the module connector, the transport pipe, the cover with sealing, the feed housing, the drive shaft, the thrust bearing, seal, the cutting head, the support bearing, the placental bearing, and the internal conveyor (screw conveyor). A cross section of the drilling / cutting head is presented in *Figure 20*.

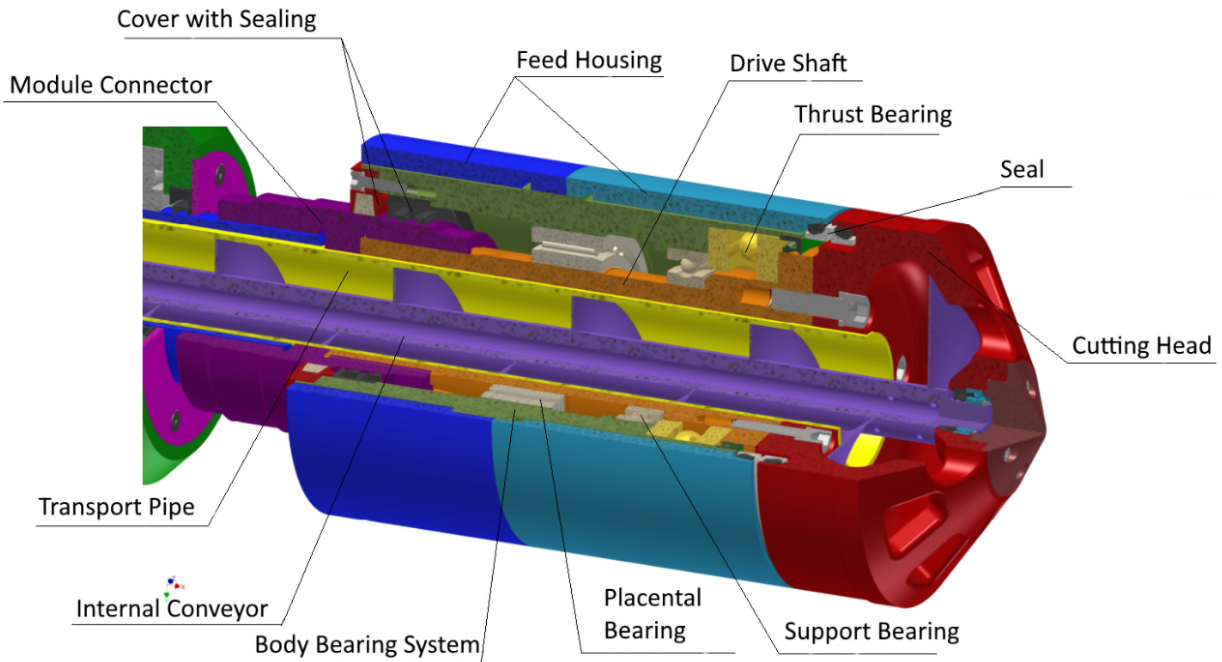


Figure 20 – Cross Section by Drilling / Cutting Head

Detailed drawings of the drilling / cutting head are presented in *Appendix E*.

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8 REFERENCES

Trawinski, T.; Szczygieł, M. and Tomas, A. (2019) *Electromagnetically Excited Torsional Vibration to Rock Drilling Support*, 2019 19th International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering, Aug. 2019, Nancy, France, pp. 29-31.

Trawinski, T.; Burlikowski, W.; Szczygieł M. et al., (2020) *Modelling of Drilling Rig with Electromagnetically Excited Torsional Vibration*, by Wydawnictwo Politechniki Śląskiej, ISBN 978-83-7880-730-8, No. 863, 2020, Gliwice, Poland.

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9 FURTHER INFORMATION

Further information about the drilling rig design is available on Silesian University of Technology, at Faculty of Electrical Engineering, in Department of Mechatronics, Akademicka 10A, 44-100 Gliwice.

Please contact Tomasz Trawiński – tomasz.trawinski@polsl.pl.

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10 APPENDIX A

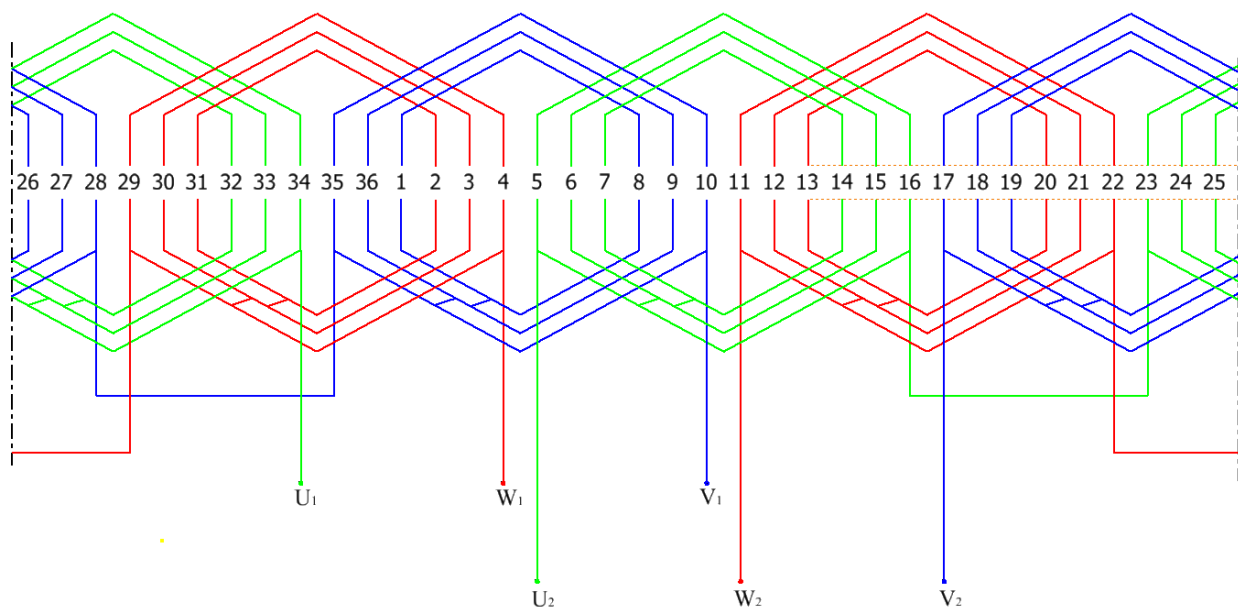


Figure 21 – Diagram of Winding of Torsional Generator and Main Motor

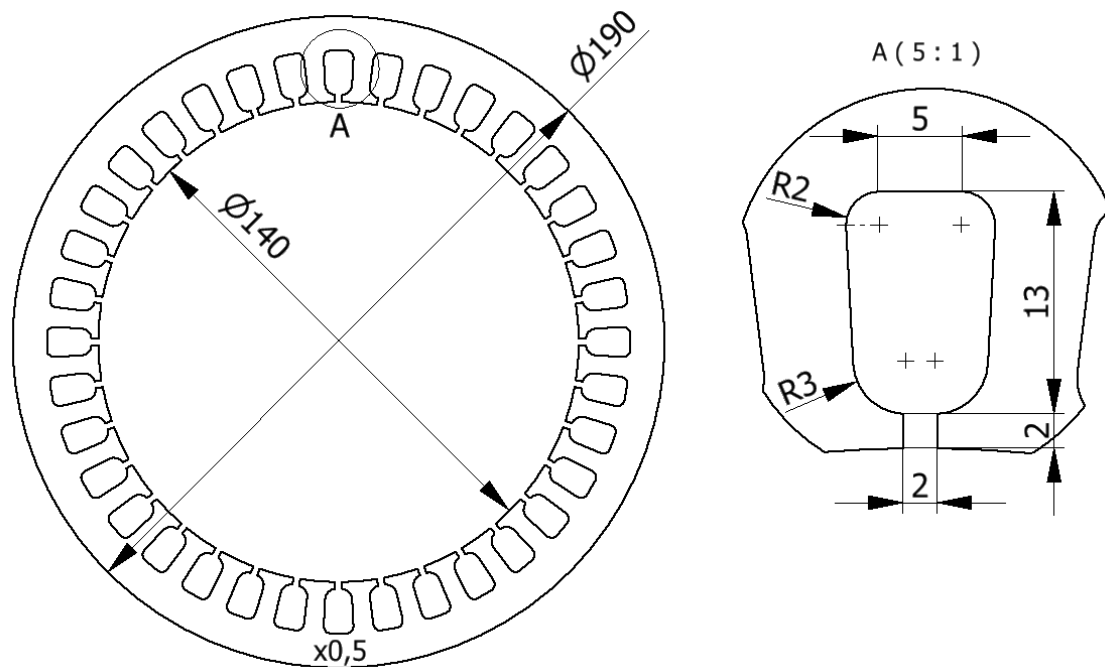


Figure 22 – Torsional Generator and Main Motor Stator Sheet & Stator Slot Dimensions

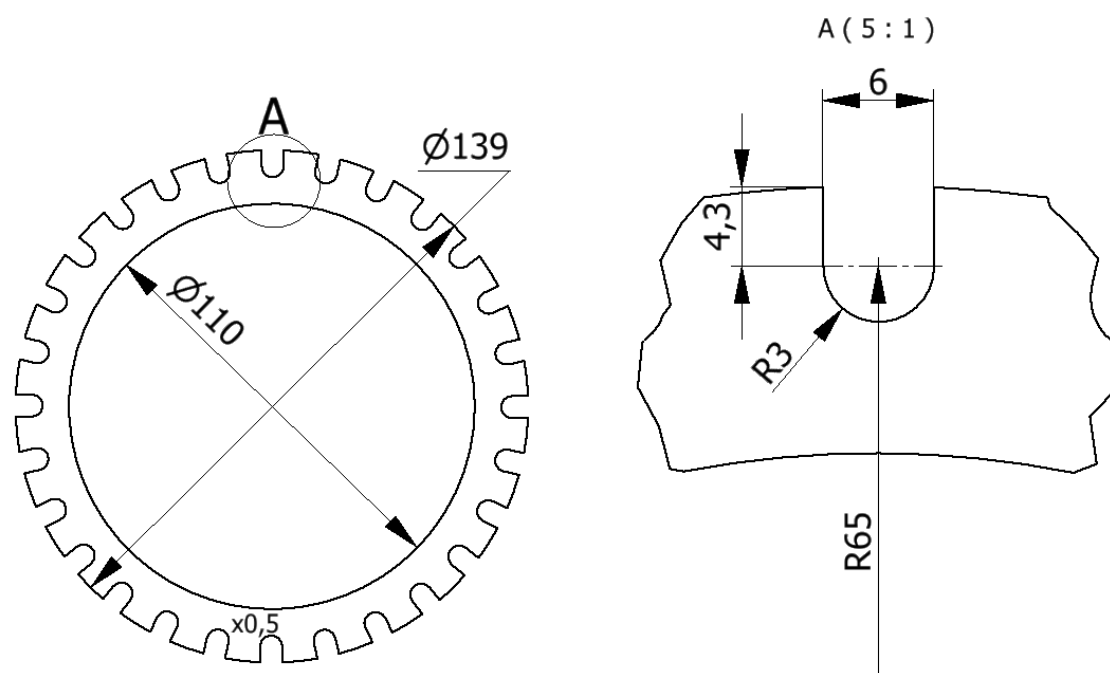


Figure 23 – Dimensions of Rotor Sheet and Rotor Slots for Torsional Generator

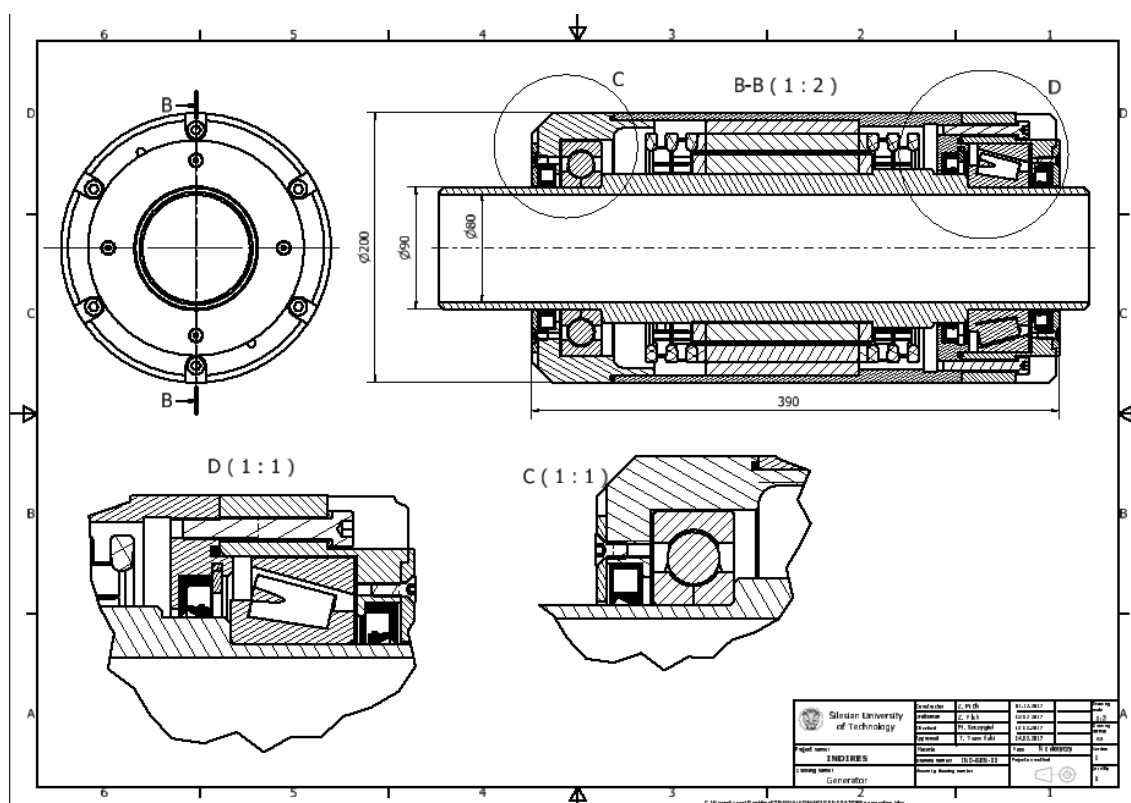
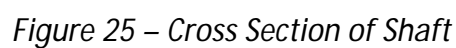


Figure 24 – Cross Section of Torsional Generator



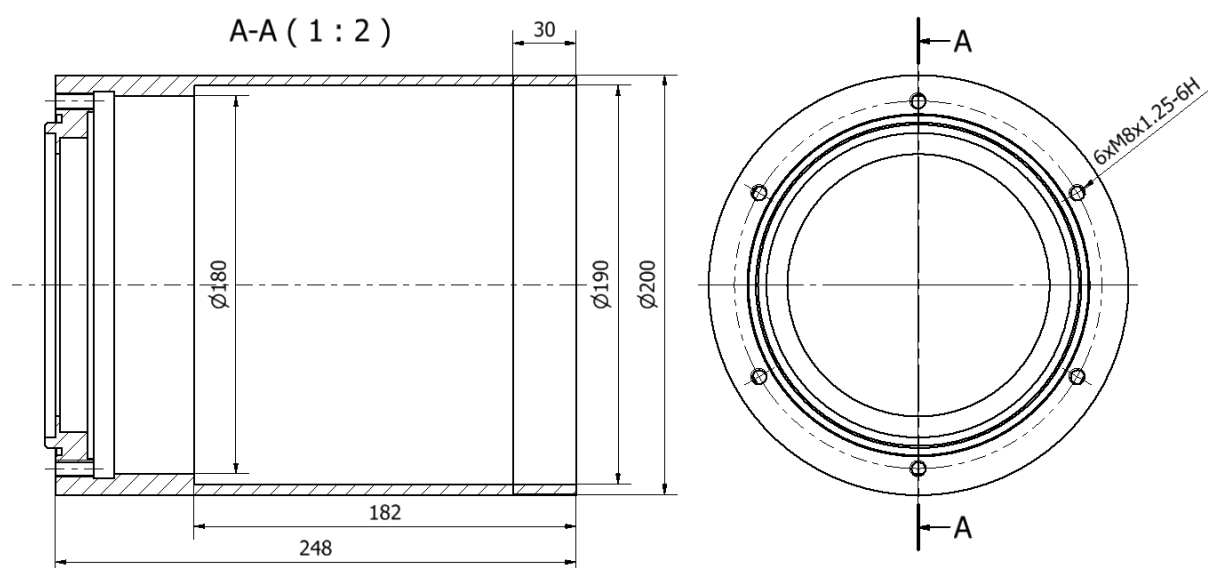


Figure 27 – Main Dimensions of the Stator of Generator Housings

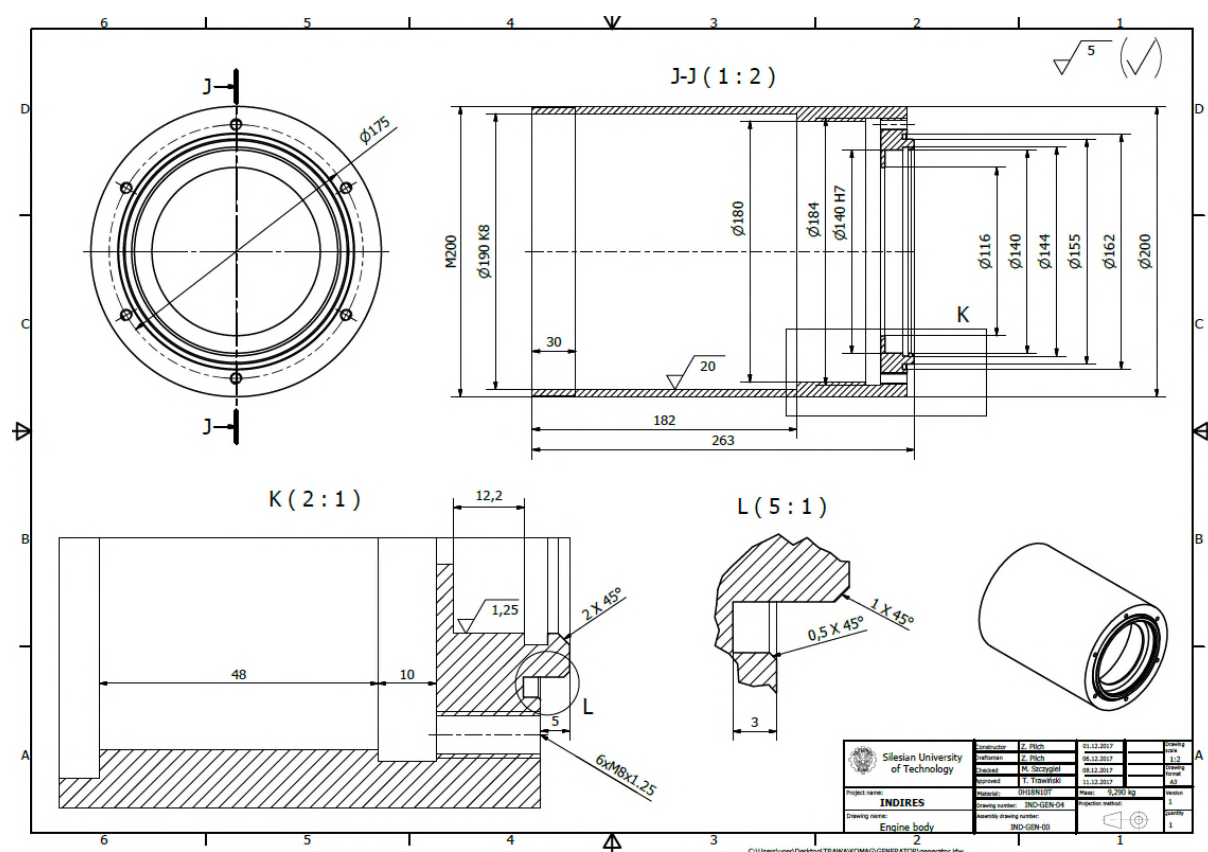


Figure 28 – Dimensions of the Stator of Generator Housings

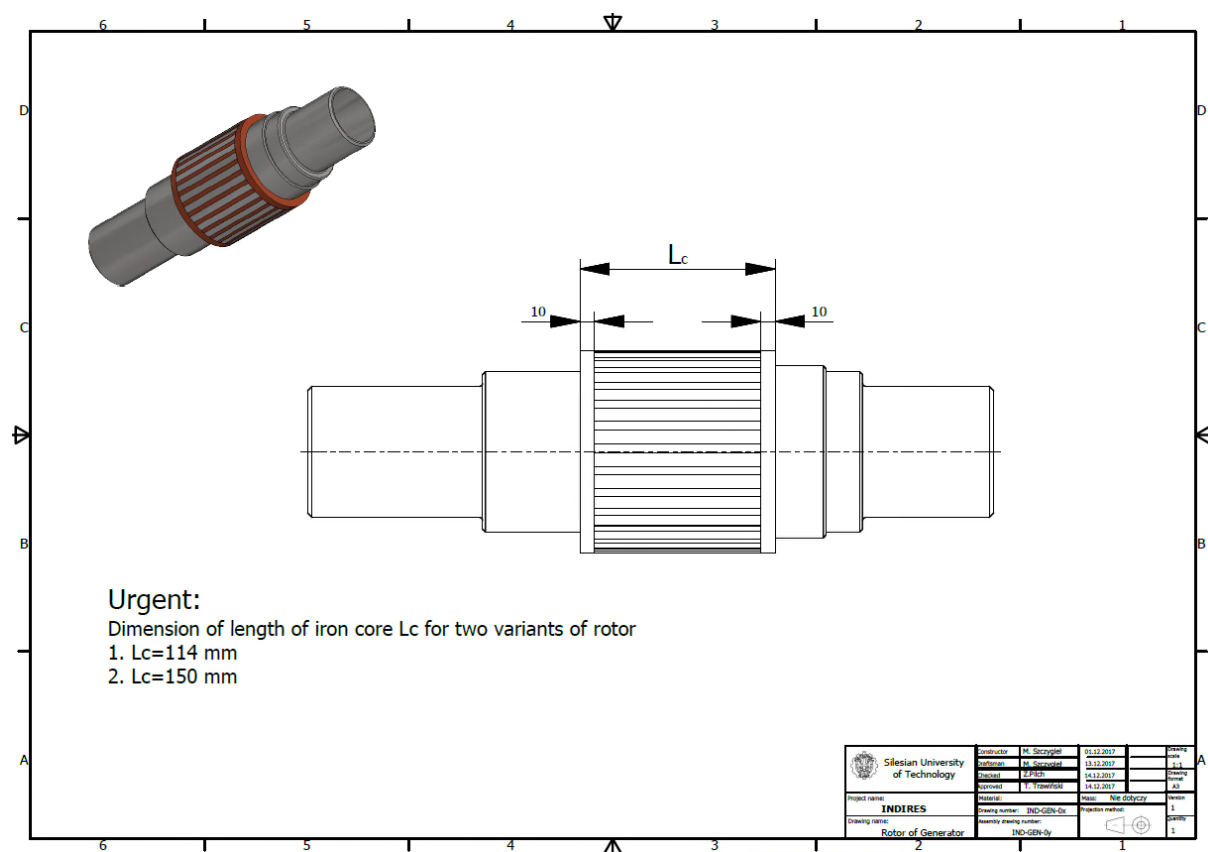


Figure 29 – Dimensions of the Rotor Iron Core for Two Variants of Iron Length

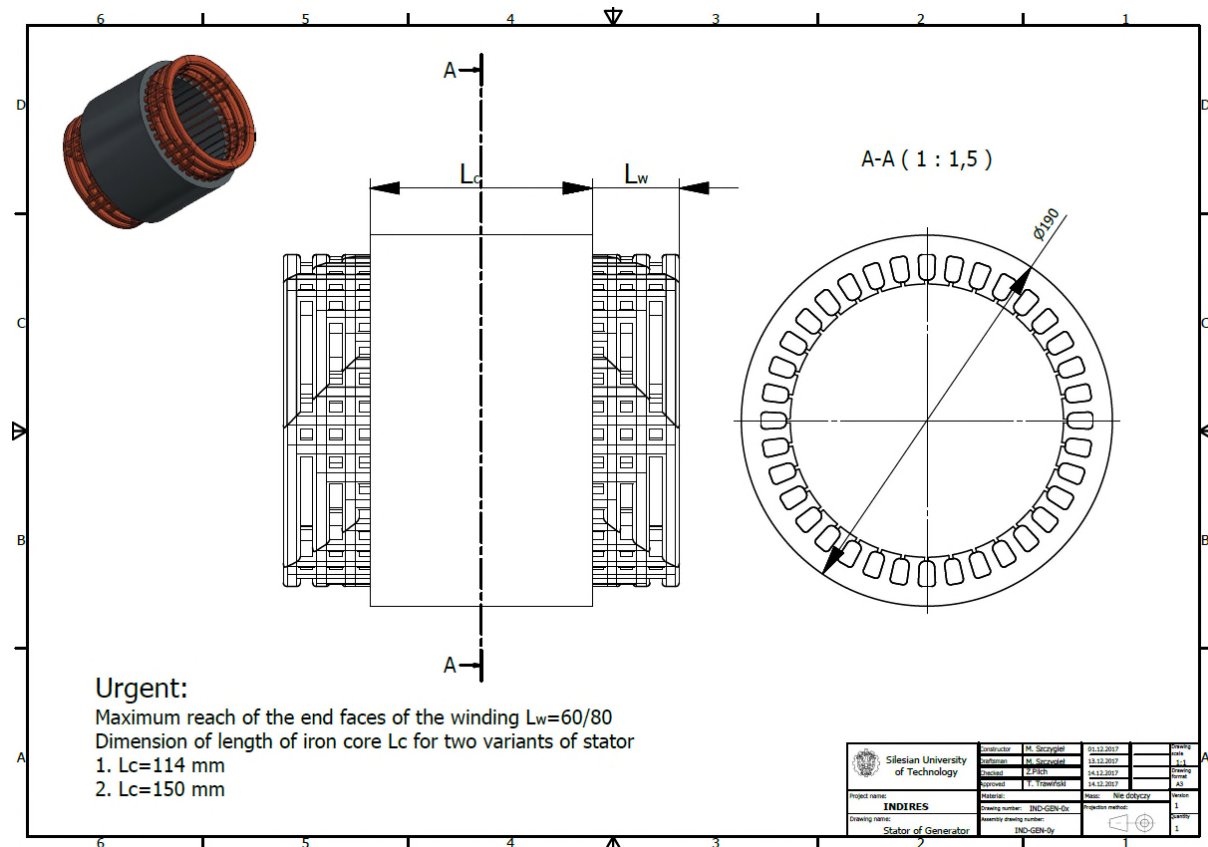


Figure 30 – Dimensions of the Stator Iron Core for Two Variants of Iron Length

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11 APPENDIX B – DROWINGS OF INDUCTON TORQUE CONVERTER

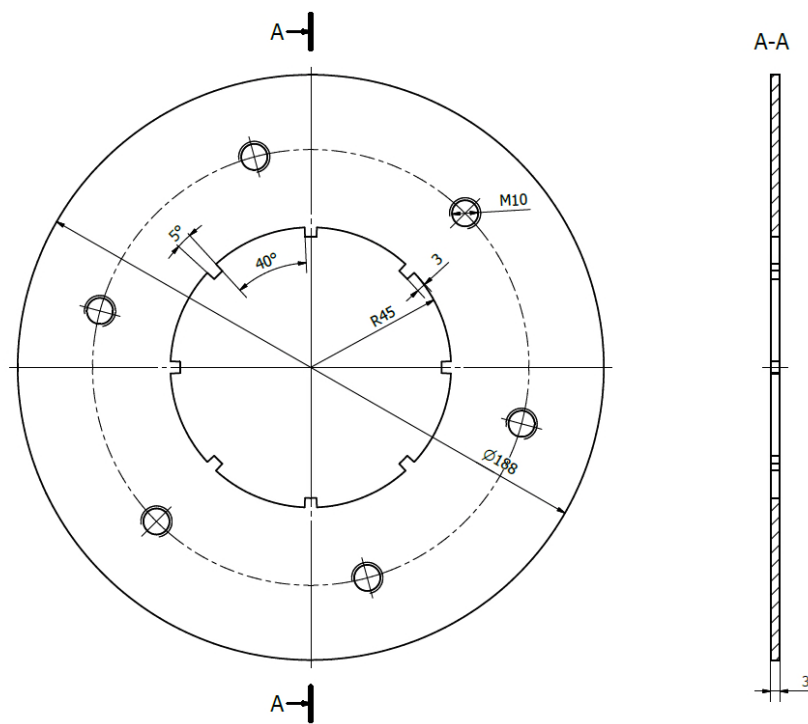


Figure 31 – Steel Disk

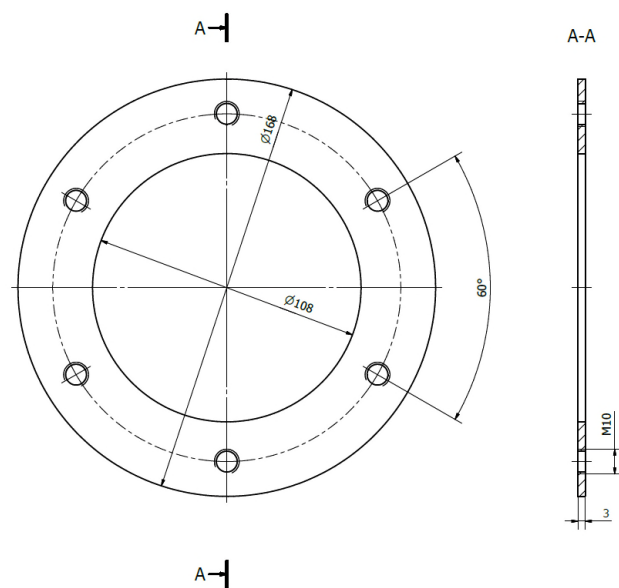


Figure 32 – Spacer Ring

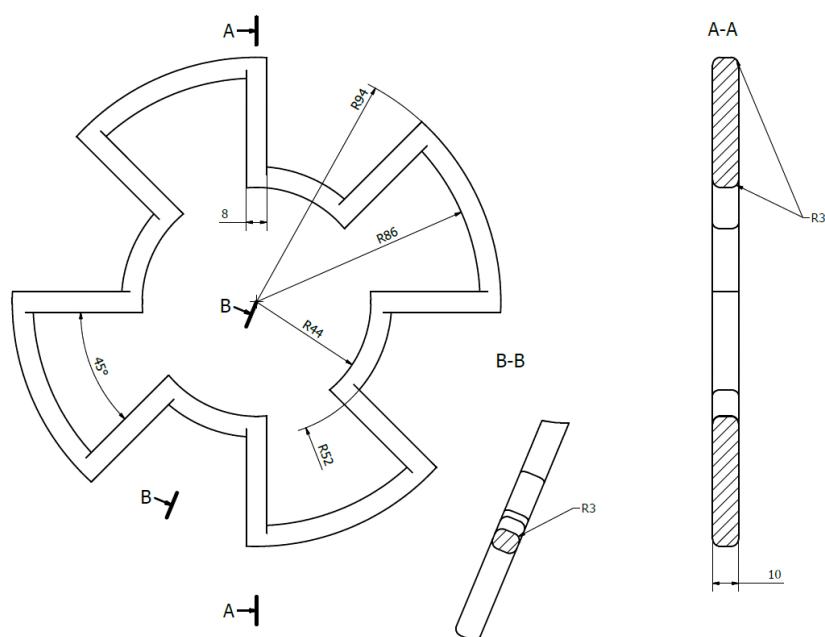


Figure 33 – Winding 1.

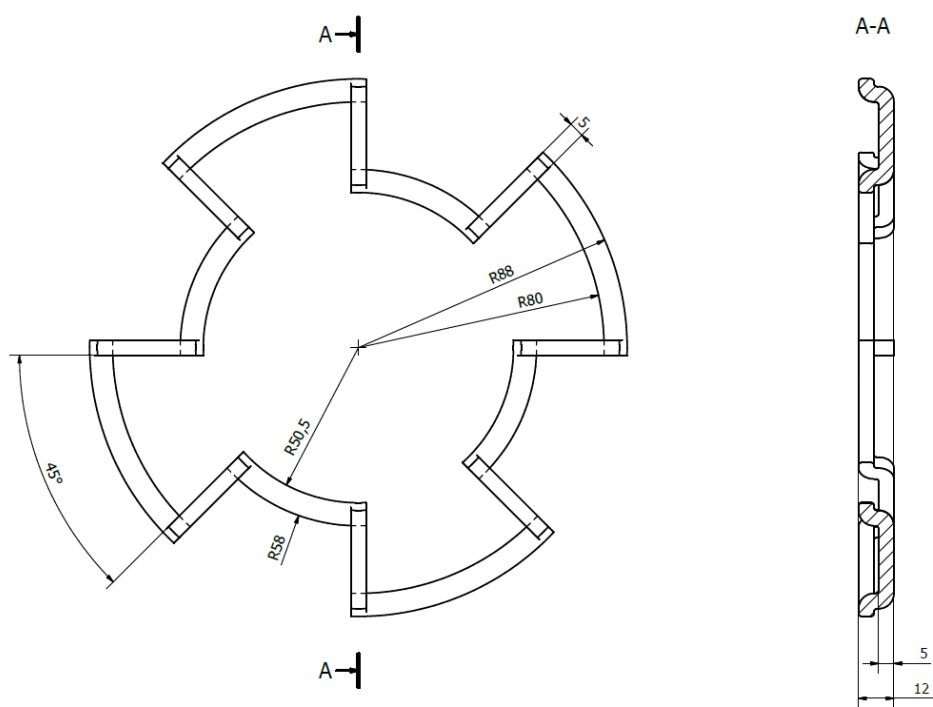
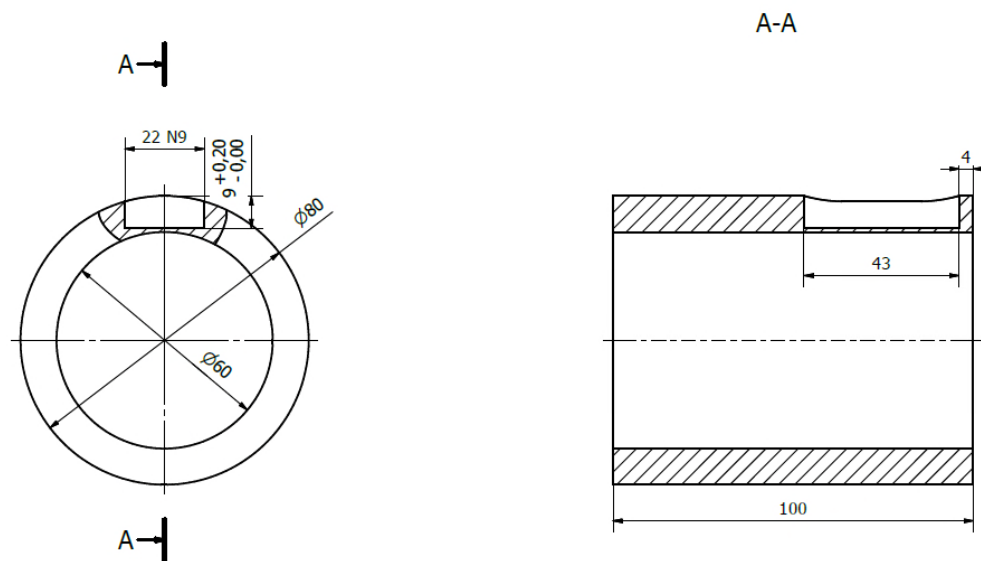
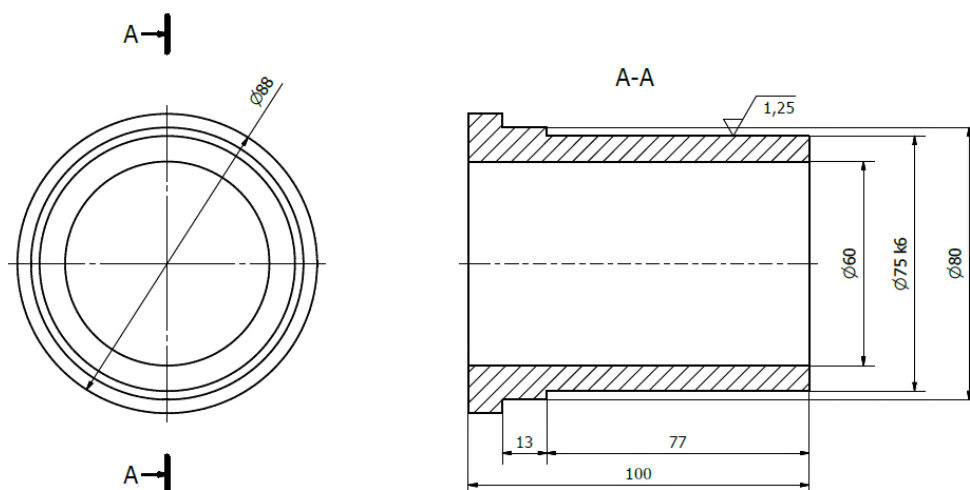


Figure 34 – Winding 2 (half of winding)
Winding consists of two of the same part, connected to each other.

*Figure 35 – Shaft 1**Figure 36 – Shaft 2*

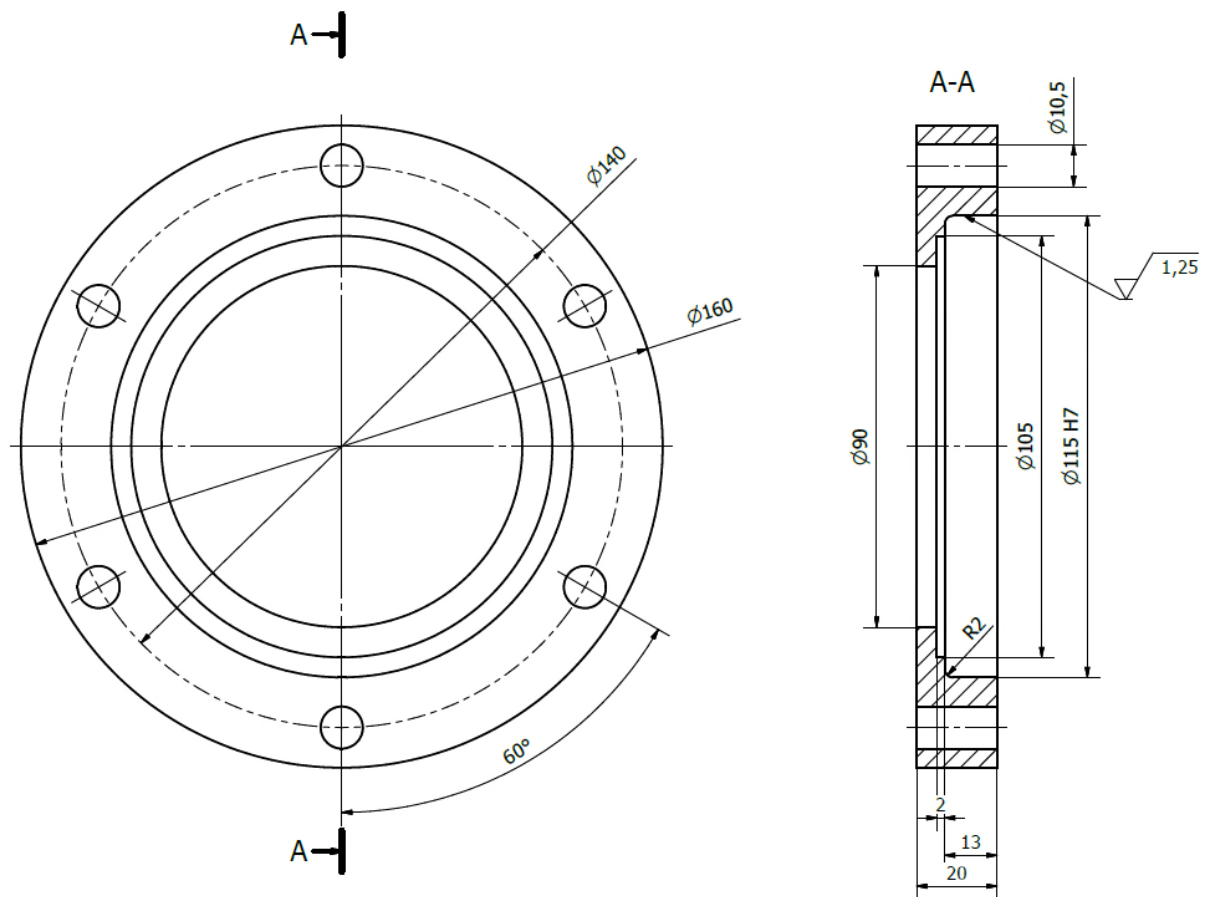


Figure 37 – Bearing Seat

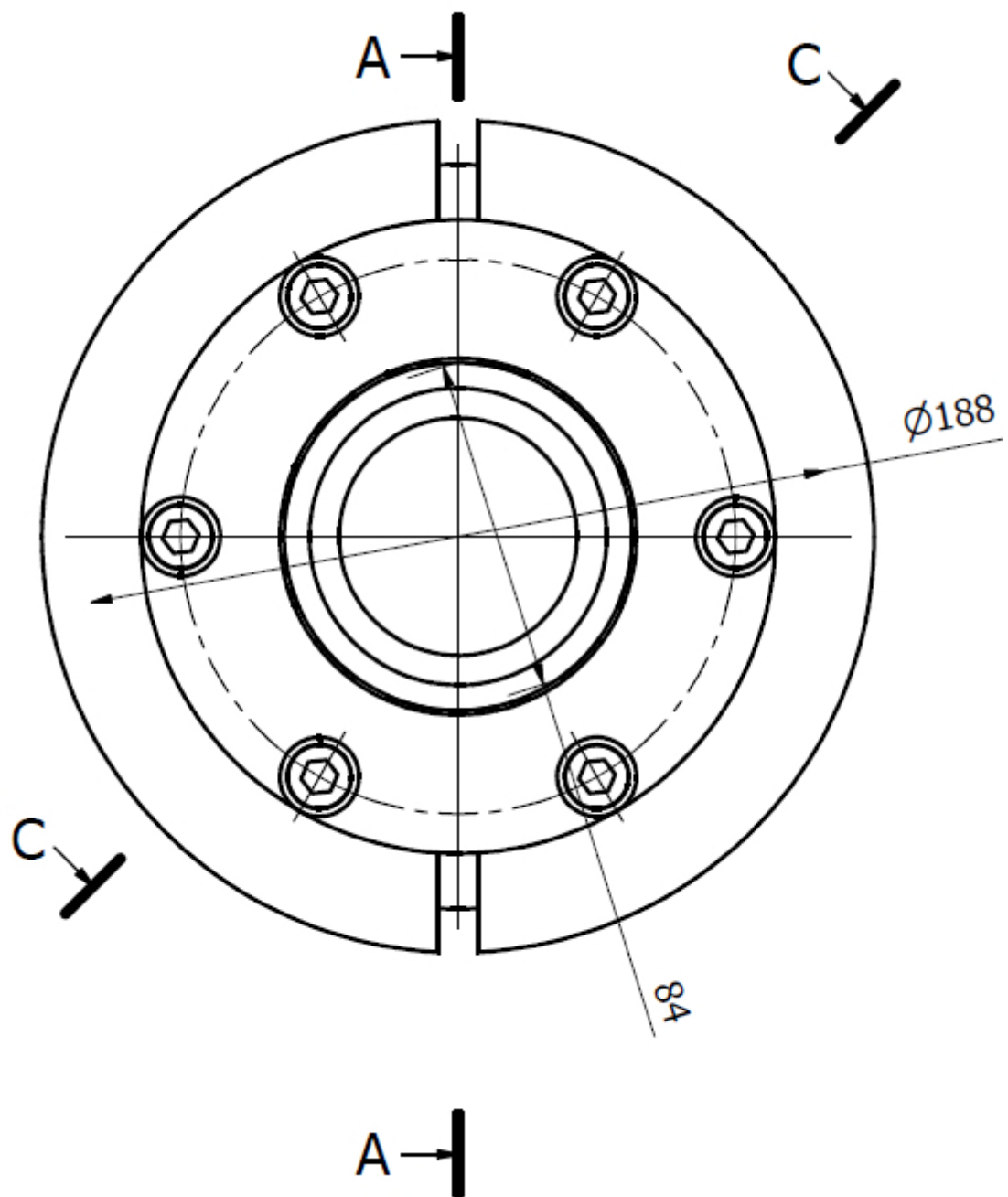


Figure 38 – Indication of Cross-sections A-A and C-C

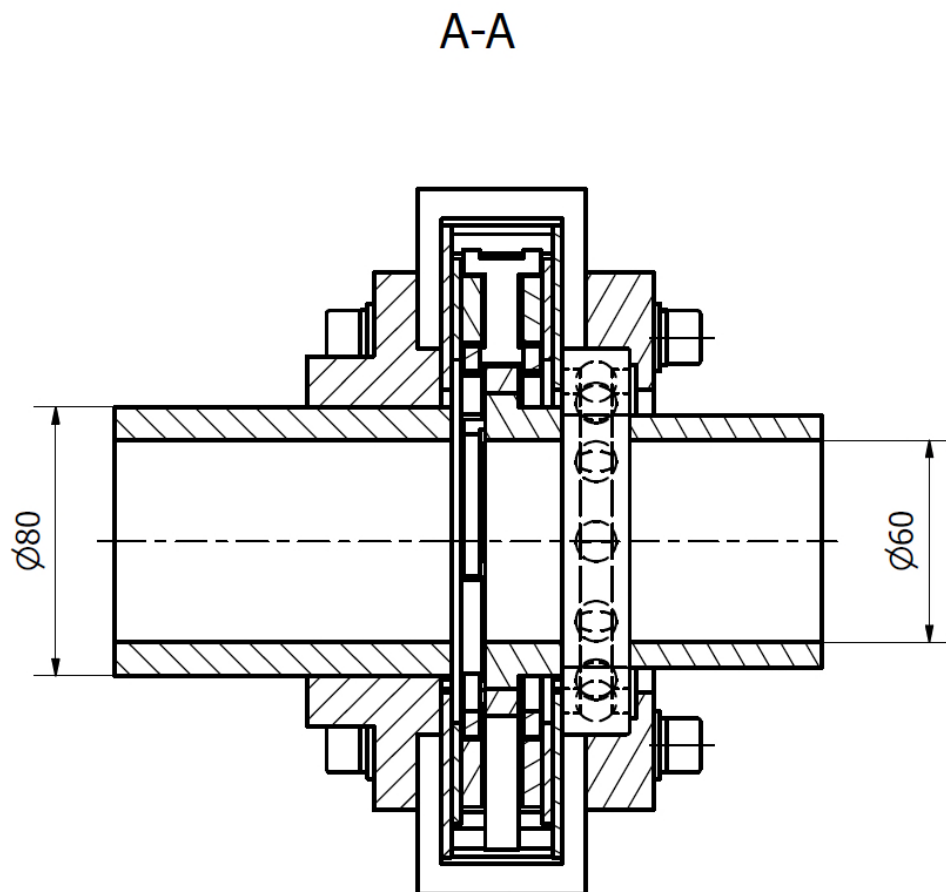


Figure 39 – Cross-section A-A and External Diameter of Shaft 1 and Internal Hole

C-C

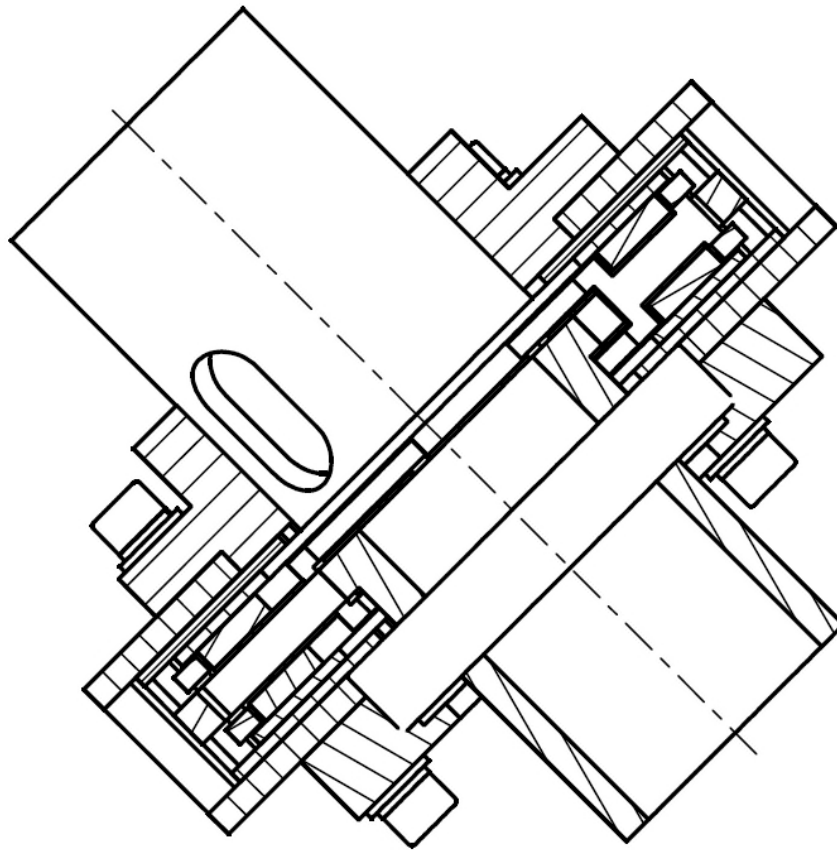
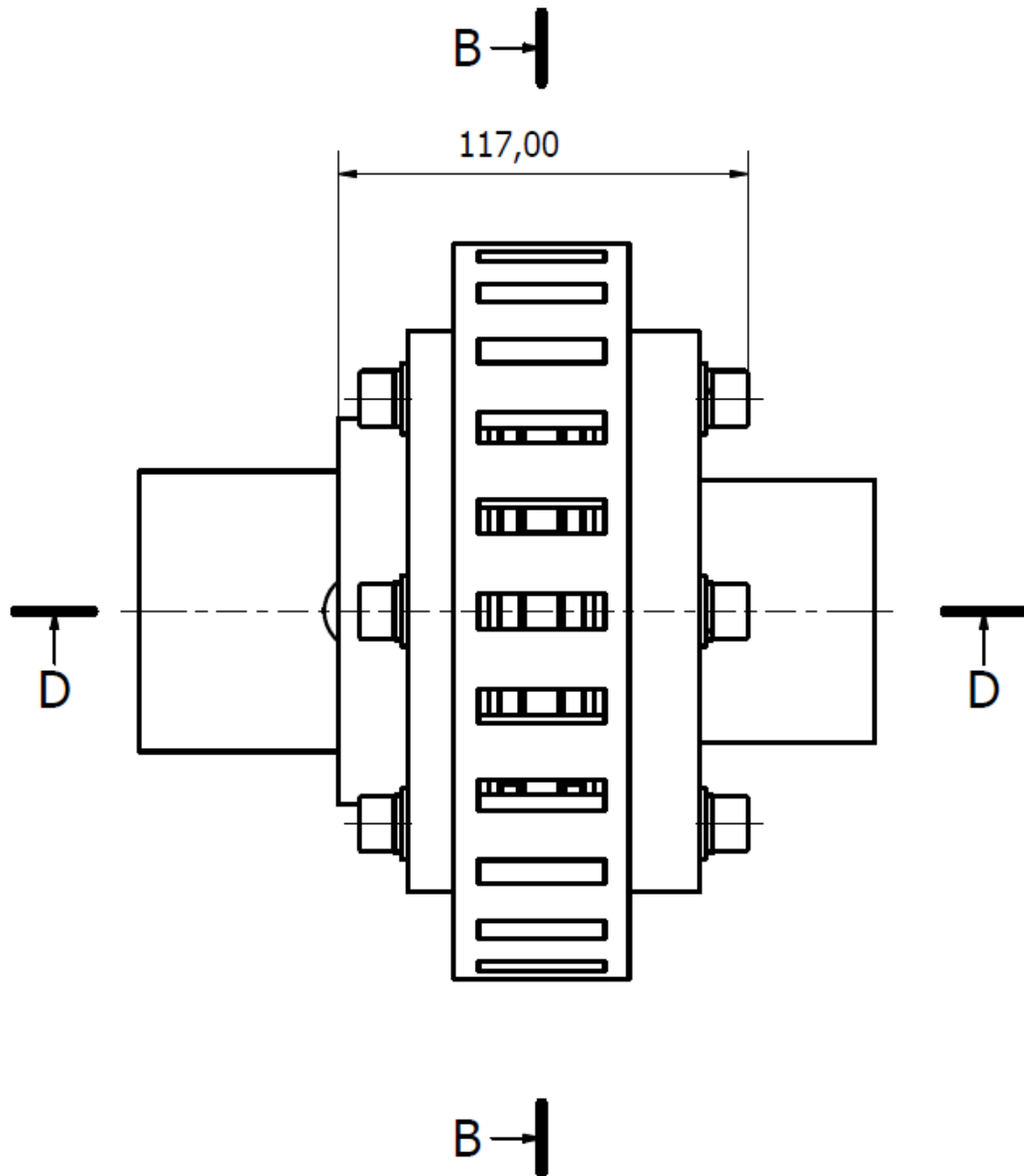


Figure 40 – Cross-section C-C



*Figure 41 – Indication of Cross-sections B-B and D-D
(Length of electromagnetic part in millimeters)*

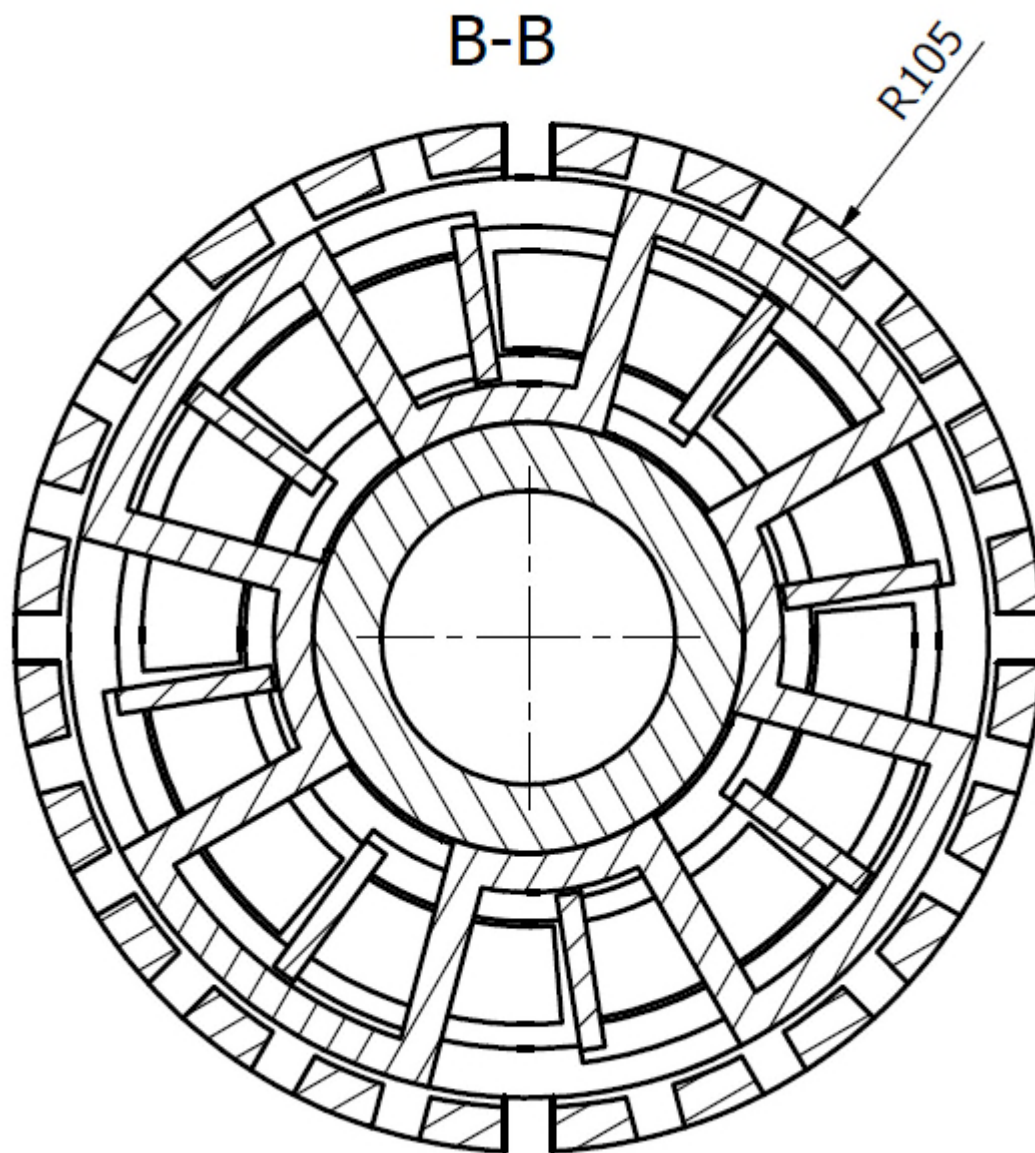
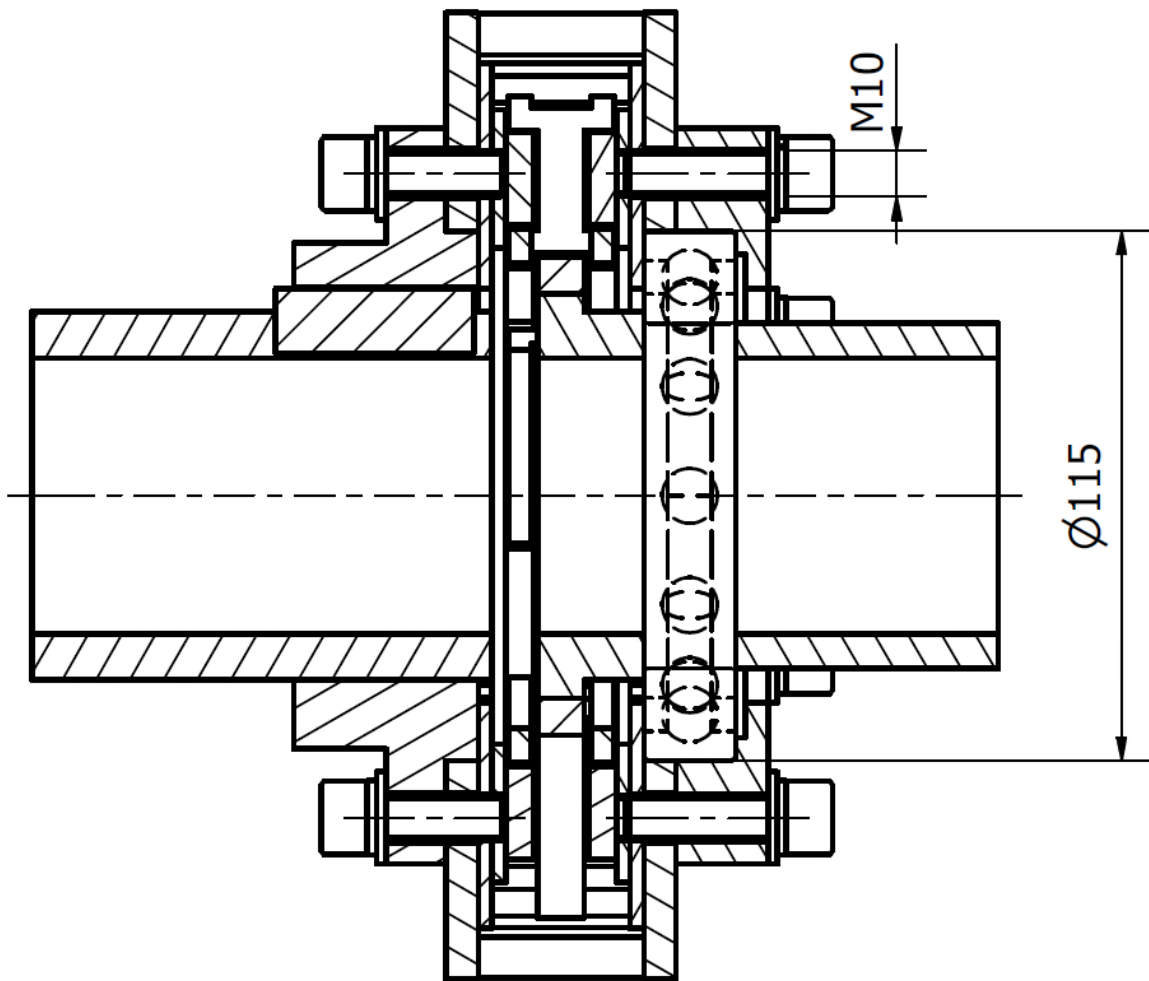


Figure 42 – Cross-section B-B, Showing Winding Cross-section and External Diameter

D-D

*Figure 43 – Cross-section D-D*

12 APPENDIX C – DROWINGS OF MAIN DRIVE MOTOR

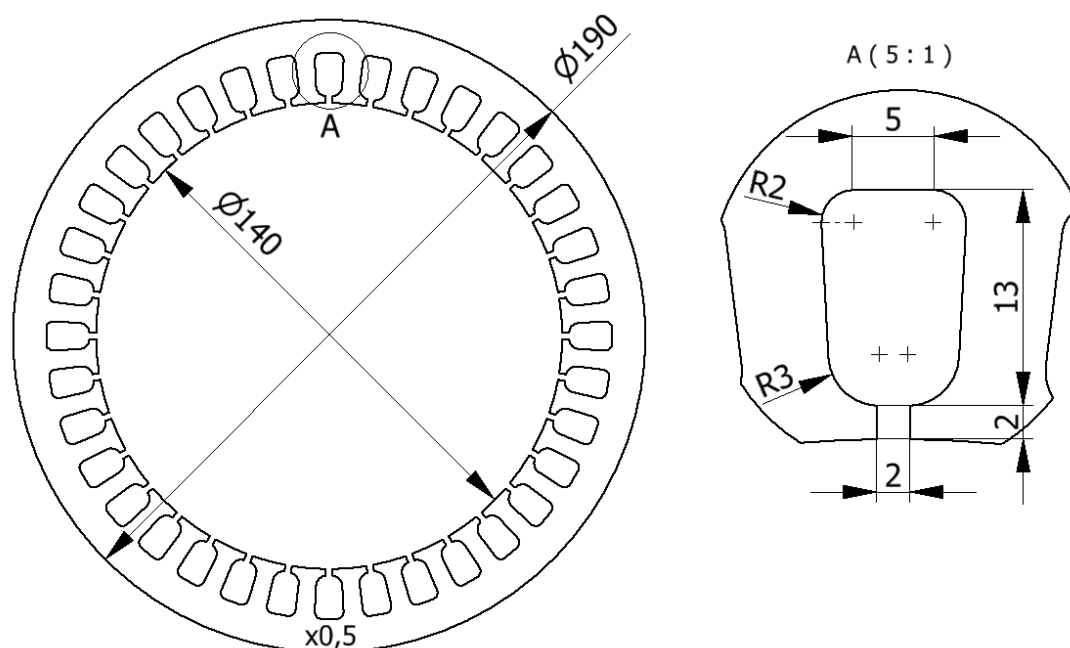


Figure 44 – Main Motor Stator Sheet & Stator Slot Dimensions

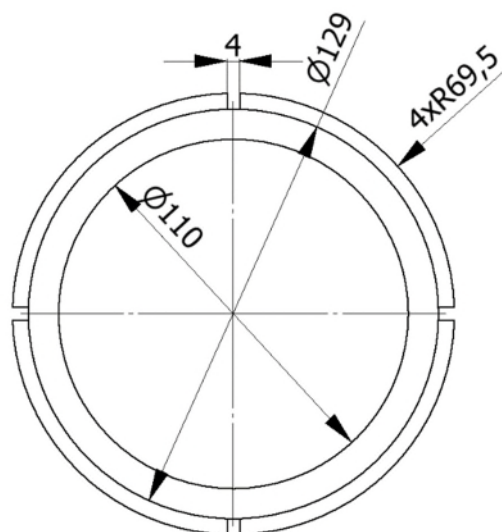


Figure 45 – Dimension of Rotor with Permanent Magnets

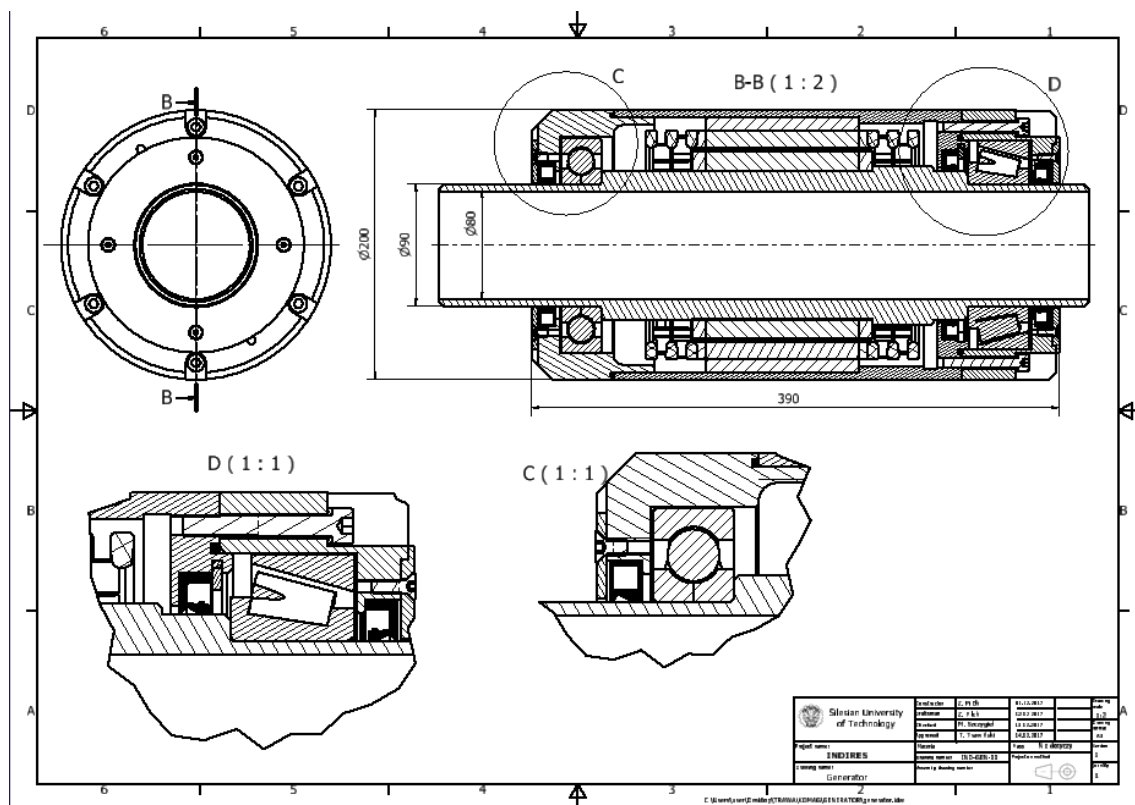


Figure 46 – Cross Section of Main Drive Motor

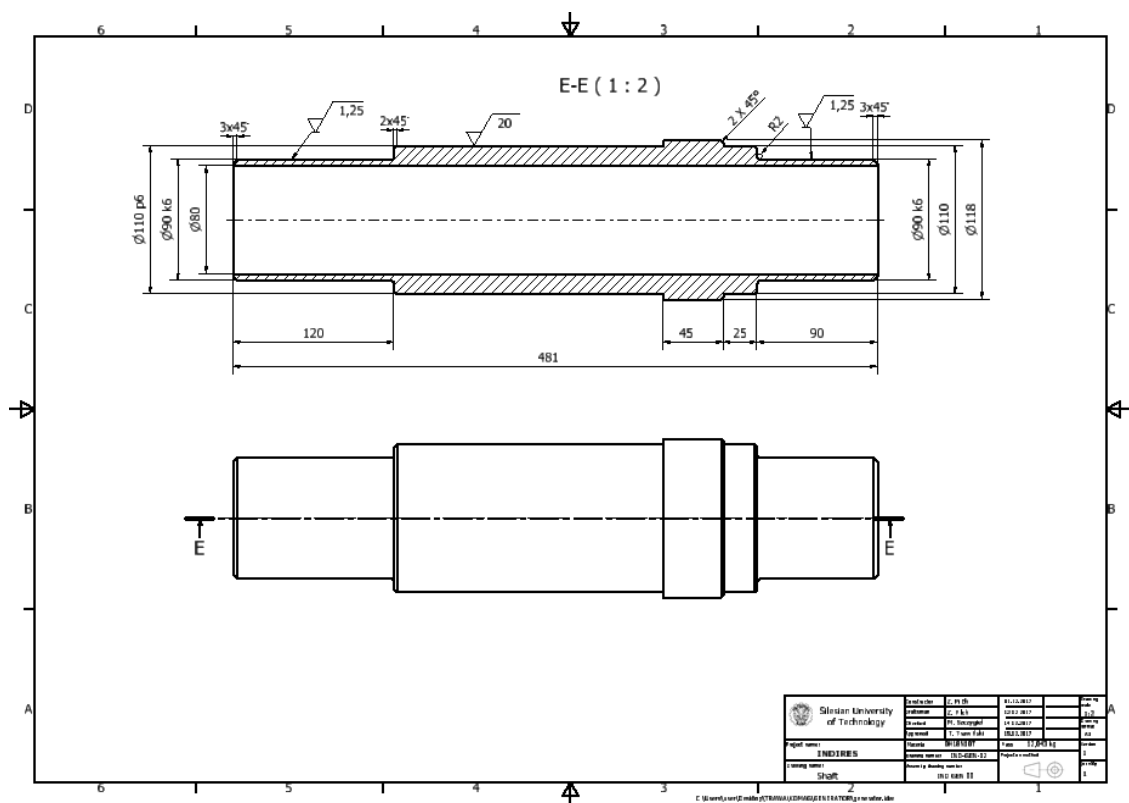


Figure 47 – Cross Section of Shaft

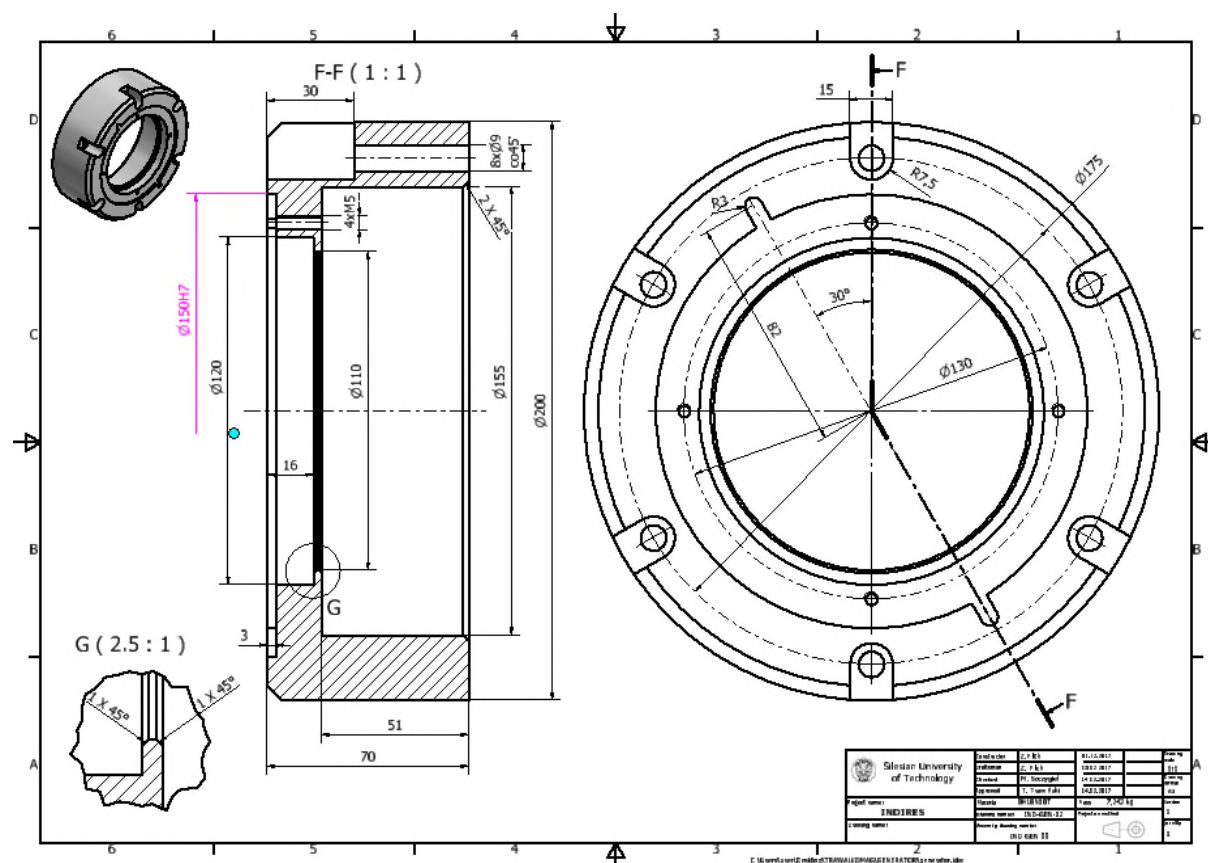


Figure 48 – Bearing Cover

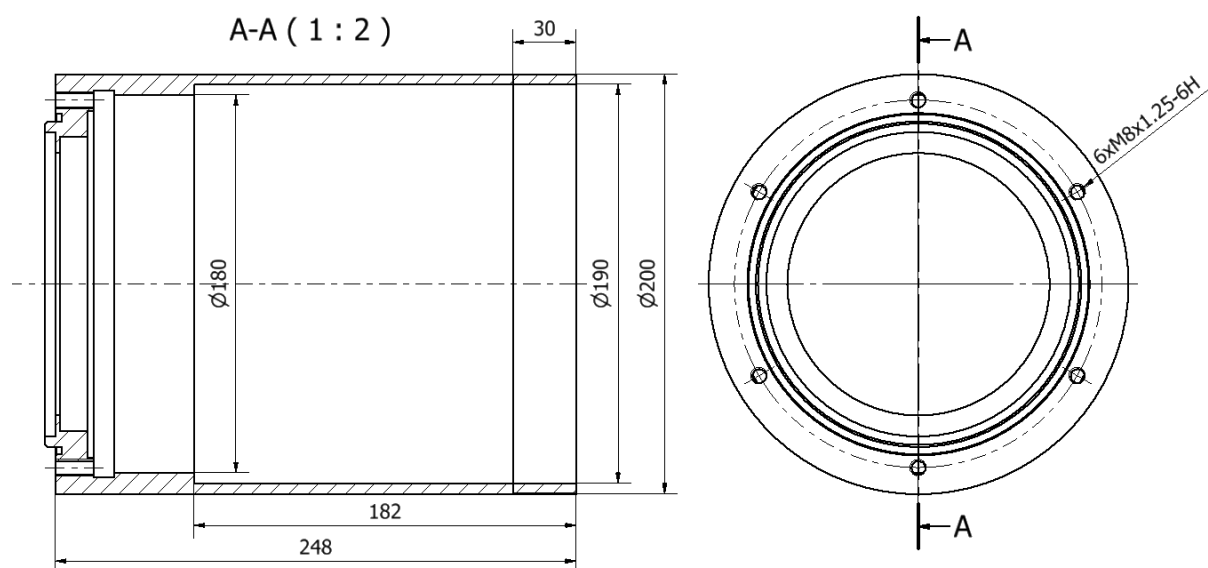


Figure 49 – Main Dimensions of Stator of Motor Housings

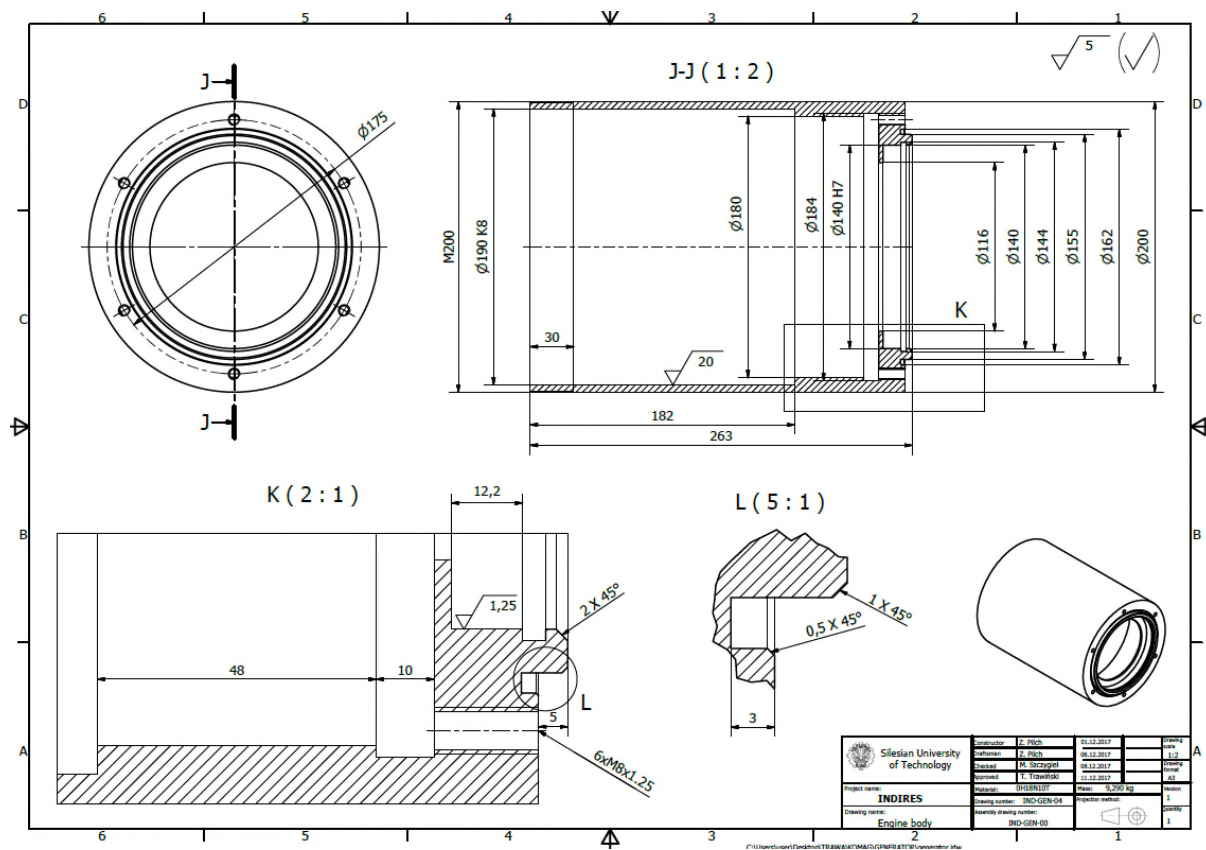


Figure 50 – Dimensions of Stator of Motor Housings

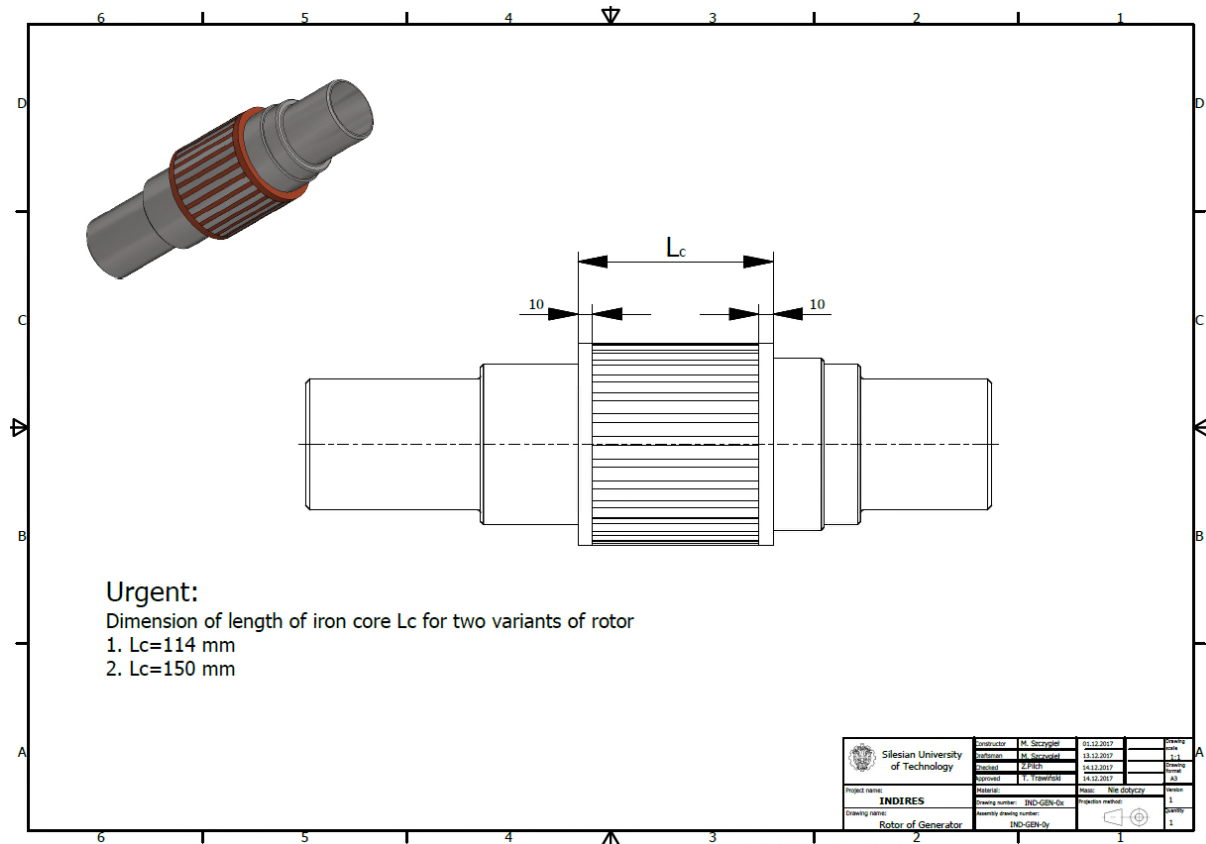


Figure 51 – Dimensions of the Rotor Iron Core for Two Variants of Iron Length

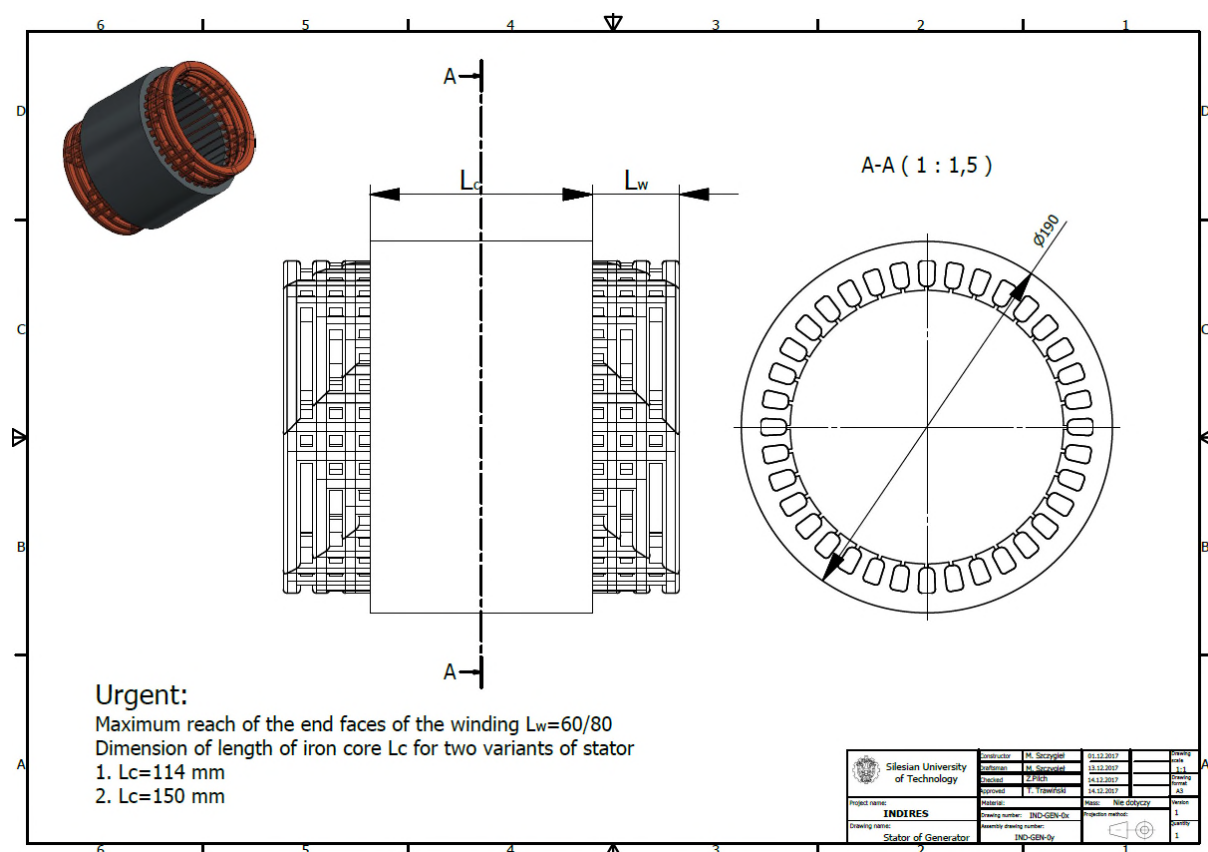


Figure 52 – Dimensions of the Stator Iron Core for Two Variants of Iron Length
(the Same Dimensions for Generator and PMSM Motor)

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13 APPENDIX D – SCREW CONVEYOR DRAWINGS

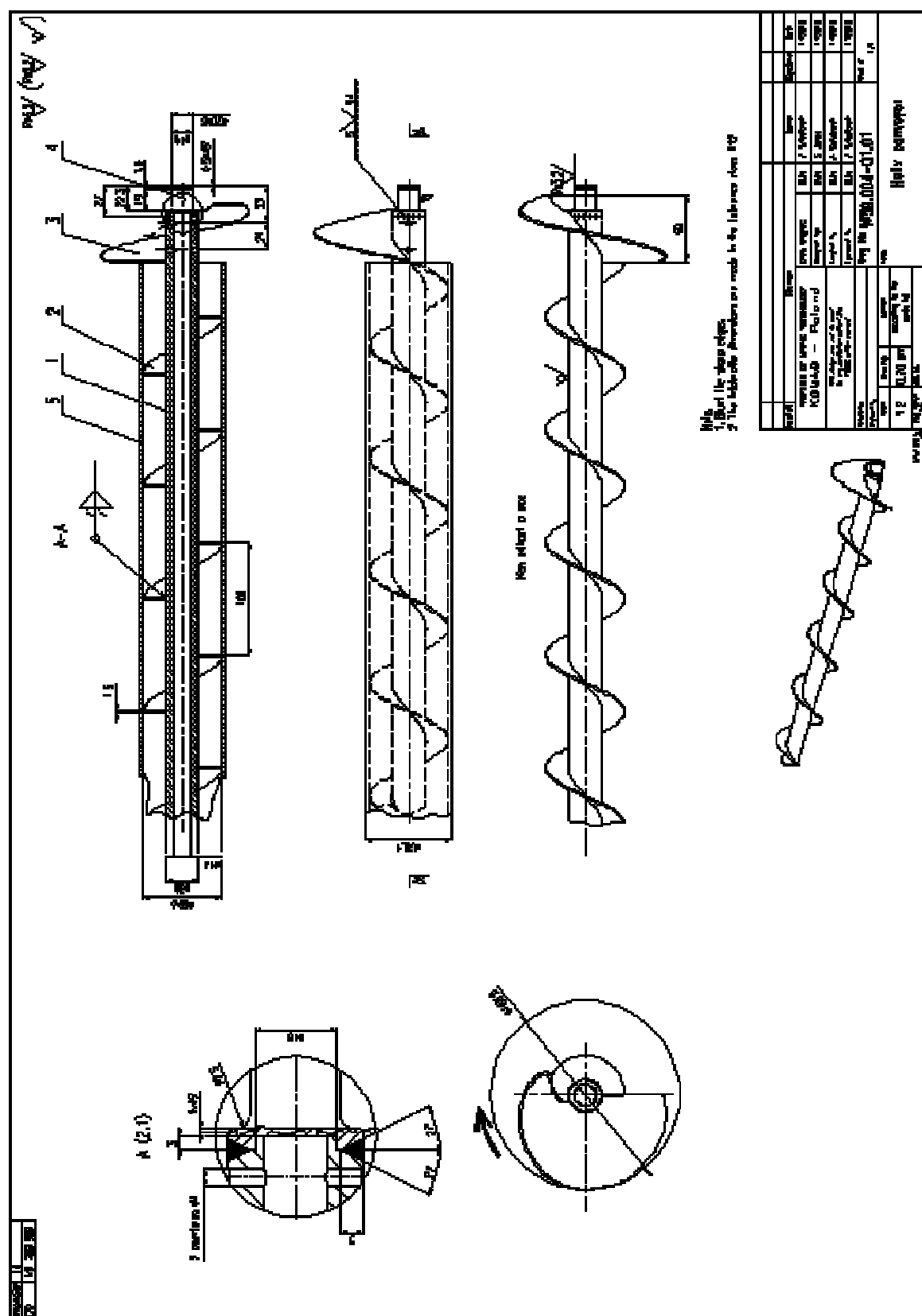


Figure 53 – Screw Conveyor Drawings

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14 APPENDIX E – DRILLING / CUTTING HEAD DRAWINGS

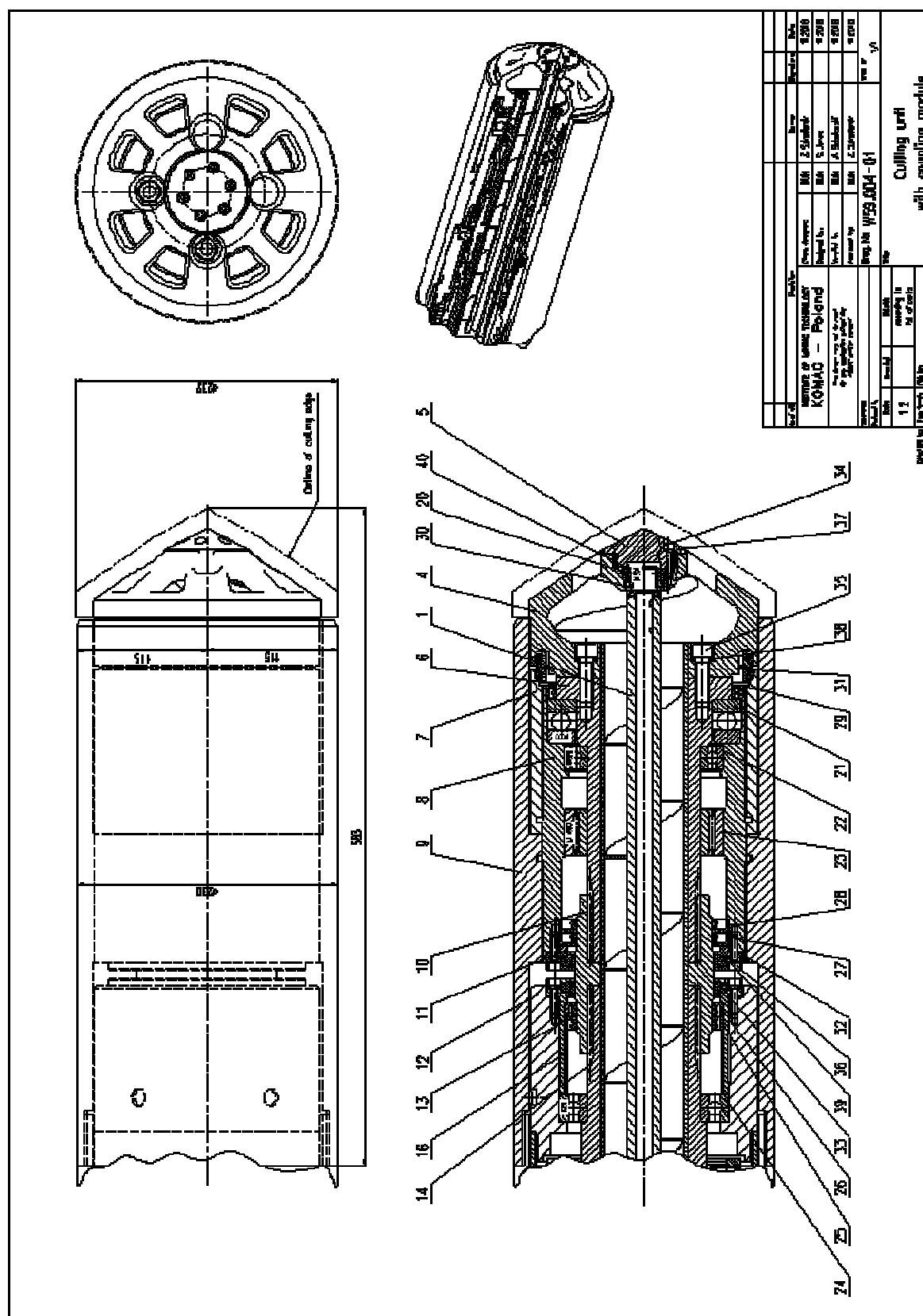


Figure 54 -Drilling / Cutting Head Drawings

