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Elektric rotary-percussion drilling machine of high power – feasibility study

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Abstract:

Rotary-percussion drilling machines are commonly used for drilling hard-to-cut and abrasive rocks. Currently, in underground mining, drilling jumbos with hydraulic drilling machines and rotary percussion drilling machines are used in chamber-and-pillar systems. The article presents results of the work aimed at assessing the technical possibilities of creating an electric rotary-percussion drilling machine with the parameters of currently used hydraulic drills. The biggest challenge is to obtain high impact energy and frequency as well as rotation speed and torque while limiting the weight and size of the drilling machine. The required parameters of the electric drilling machine were the parameters of the hydraulic drilling machines used at KGHM Polska Miedź S.A. Known and applicable design solutions for electric drilling machines were analysed including the reported inventions in Poland and abroad. Then, three design solutions were selected and dynamic model tests were carried out, the main goal of which was to estimate the required torque, which, combined with the rotation speed, determines the power of the electric motor. As a result, the solution was obtained, which in terms of weight and dimensions does not differ significantly from the hydraulic drilling machines, while at the same time enabling the achievement of similar operational parameters that determine the mechanical drilling speed.

Keywords: simulation tests, rotary percussion drilling machine, hydraulic drilling machine, electric drilling machine, underground mining,

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1. Introduction

Rotary percussion drilling machines use different drives to generate impact and rotation. There are known the solutions for hydraulic, pneumatic and electric drilling machines. However, drilling machines used on the drilling jumbos are expected to have high impact energy and frequency with high torque. Only hydraulic drills meet these requirements. However, for much lower parameter values, pneumatic or electric solutions are used.

There are known the solutions for mine electric drilling machines, but due to a number of disadvantages, especially big weight, large dimensions and high failure rate, they were not developed and were quickly replaced by hydraulic drilling machines [1]. Electric rotary-percussion drilling machines have not the parameters of hydraulic drilling machines, which are crucial in mining processes. However, in the case of drilling machines used in the construction, road and private use industries, electrical solutions are very popular. In the case of mining solutions, in recent years only one electric drilling machine was available, but with a low impact energy.

2. Analysis of state of the art

A review of patent publications allowed us to find technical solutions and utility models in the field of electric rotary percussion drilling machines. These solutions can be divided into three types. The first are the solutions that create an impact effect using various types of cams connected to a coil spring. These solutions are mainly used in hand-held power tools with low weight and relatively low impact energy. These patents belong to global companies specializing in the production of power tools, such as Makita Corp, Robert Bosch GmbH, or Black&Decker.

Another type of solutions are the devices using the magnetic field. Electromagnets generate impact piston impacts, and the electric motor is responsible for the spindle rotation. These inventions therefore require power supply for both electromagnetic units and the electric drive that rotates the tool. This solution is used, for example, by FlexiDrill.

The last type are solutions that cause a stroke by a moving piston in a cylinder with a spindle at the end. The electric drive, through a gear unit, rotates the crankshaft to which the piston is attached. This piston presses on the spindle, not directly, but through a coil spring or air cushion, which protects it against direct impacts. In these inventions, the same electric drive causes the impact and rotates the spindle. HILTI is one of the companies using such a solution.

Of all types of inventions, where the impact is generated by a crankshaft and a piston with an air cushion were included in further analysis. This solution offers relatively greatest performance with a relatively simple and well-known design. However, for the research purposes, two other solutions were also considered: with a shaft and an inclined disc and with an electric linear motor. For the first solution, the drive shaft has a disc with a pin at an angle in relation to its axis. The disc with a pin is installed on a shaft. The rotation of the shaft causes a change in the angle of inclination of the disc, as a result of which the end of the pin moves back and forth. The movement is transmitted to the piston. The piston is separated by an air cushion with a impact piston of a specific mass. The piston drives the impact piston, which hits the rod holder. The same shaft simultaneously transmits torque to the rod holder, generating continuous rotation. The third solution is to use two electric motors, one rotary and the other linear. They generate the impact of the ram and the rotation of the tool independently.

Mine electric rotary-percussion drilling machines were historically used for a very short time. This was related to their disadvantages, the solution of which was not sought because hydraulic drilling machines were devoid of them. An example of this is the Pneumelectric drilling machine (Fig. 1). Generally, each electric drilling machine had a crankshaft with a connecting rod that generated a reciprocating movement. In the initial solutions, the piston and the impact piston were separated by a spring, and in later solutions, as now, by an air cushion.

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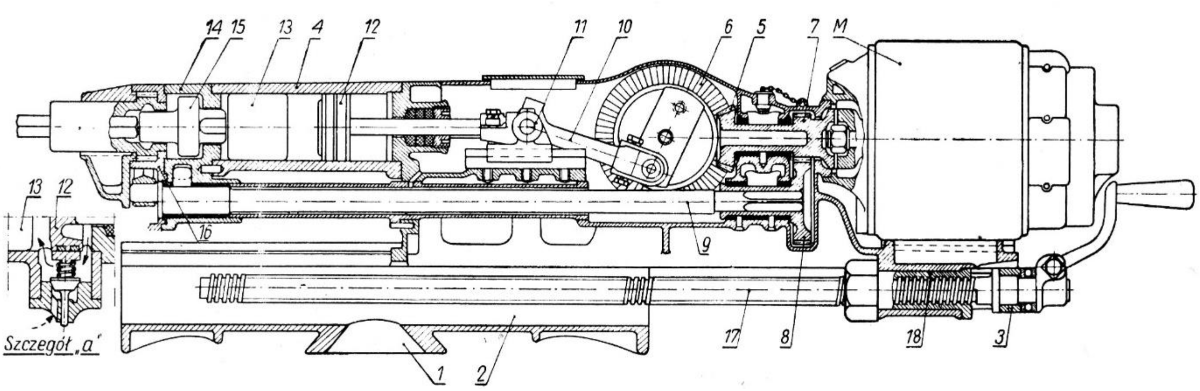

Fig. 1. Mine electric rotary - percussion drilling machine Pneumelectric [2]

In 2018, the start-up Lekatech was founded in Finland. Lekatech offers an electric impact hammer mounted on excavators. According to the company, the technology used is significantly better than the hydraulic hammers. A Linear Induction Motor (LIM) was used, which is the most important component of the hammer. The advantage of the hammer is the ability to control the impact energy and frequency of impacts. The hammer has a high impact energy up to 1500 J, but with a very low frequency from 1 Hz to 15 Hz and a large mass of approximately 450 kg [3, 4].

Currently, there is a well-known mine electric rotary-percussion drilling machine with a crankshaft - Hilti TE MD-20, shown in Fig. 2. It is a drill powered by an asynchronous motor with a low power of only 2.2 kW. According to the catalogue, the energy of a single impact is 28 J and the torque is 100 Nm. The tool moves at a rotational speed of 205 rpm. The drilling machine weighs 23.5 kg and is a hand-held drilling machine, but operated from a support [5].

However, in the literature, only some studies can be found in the field of simulations and general model tests of rotary percussion drilling machines [6, 7, 8]. There are many studies available on dynamic simulation studies of mining machines [9, 10, 11].

Fig. 2. Hilti TE MD20 drill and 3D model of the drill mechanism from the Hilti catalogue [2]

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3. Assumption for the electric rotary percussion drill

Feasibility study of a high-power electric rotary-percussion drilling machine was the work objective. As well as estimating the power of the electric motor and determining approximate overall dimensions and minimum weight. Hence, the model was developed using a number of simplifications that, to a greater or lesser extent, affect the obtained results. The simplifications were adopted in such a way as to obtain the best possible results. Therefore, many unfavourable phenomena, such as air flow resistance or friction of interacting components, were omitted. The results of the simulations should be treated as indicative. Due to the assumptions, in reality the drilling machine will not achieve the expected parameters for the assumed power. This means that the specified power is the minimum required for ideal conditions. Similarly, regarding the size and weight of the drilling machine, the estimates given are a lower limit.

Important is the method for determining the impact energy of the drilling machine. Manufacturers determine the impact energy in different ways, measuring it at the measuring stations or determining its value based on the mass and speed of the impact piston. As part of the work, the model tests were carried out, so taking into account the lack of detailed information on the method of determining the impact energy by various manufacturers, the impact energy was defined as the kinetic energy of the impact piston with mass m_b and velocity v_b at the moment of impact, as:

$$E_u = \frac{m_b \cdot v_b^2}{2} \text{ [J]}$$

Many different solutions for electric rotary percussion drilling machines are known, especially among patents. In practice, only two main solutions are used - with a crankshaft and with an inclined disc, and such solutions have been analysed. Additionally, use of a linear motor, as in the above-mentioned impact hammer has been analysed.

The first stage of the work was to determine the parameters of the electric drilling machine based on data from hydraulic drilling machines used at KGHM Polska Miedź S.A. and which meet the expectations when drilling the blast holes. The key parameters are the energy and frequency of the impact as well as the speed and torque of the tool. For comparison purposes, weight of the drilling machine is also important. Several model+s of drilling machines were analysed and the following parameters were collected based on the catalogues:

- MM-20 f = 67 Hz, M = 796 Nm, n = 250 rpm, E=400-500 J, m = 177 kg
- HC109 f = 40-60 Hz, M = 1000 Nm, n = 190-220 rpm, E=440 J, m = 142 kg
- HC109 f = 40-60 Hz, M = 457-1275 Nm, n = 120-300 rpm, E=449 J, m = 142 kg
- HC95LQ f =57 Hz, M = 764-955 Nm, n = no data, E=430 J, m = 196 kg

From the point of view of the impact mechanism operation, the most important assumption was to assume the required mass of the impactor, its stroke and speed at the moment of impact. This information is difficult to be obtained. Taking into account the diagram of the MM-20 drilling machine available in the catalogue, it was determined that the steel ram for this size weighs approximately 6.7 kg. Based on the analysis of available literature in this area, these parameters, including the speed of the impact piston at the moment of impact, were confirmed.

One of the articles presented the results of testing the hydraulic percussion drilling machine (Fig. 3) [12]. Based on these results, it was determined that for a 5 kg impact piston, the stroke is 53 mm, the maximum impact piston speed is 12 m/s (at the moment of impact), and the impact frequency is about 60 Hz ÷ 65 Hz.

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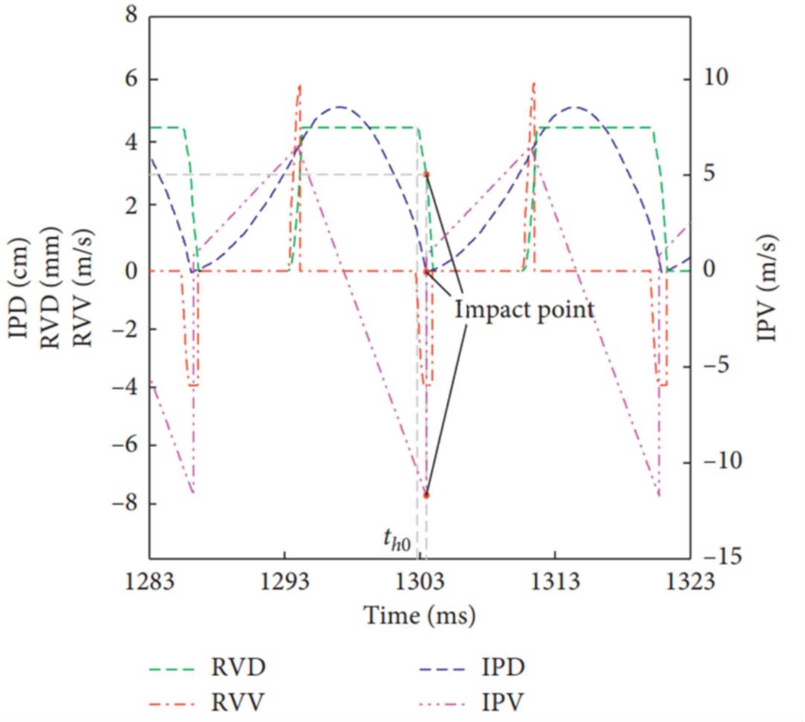

Fig. 3. Results of testing the hydraulic rotary-percussion drilling machine [12]
IPD: impact piston displacement); IPV: impact piston velocity; RVD: reversing valve displacement RVV: reversing valve velocity

Due to the above, the following parameters of the electric rotary-hammer drilling machine were adopted:

- impact frequency f = 60 Hz,
- impact energy E = 450 J,
- tool rotation speed n = 250 rpm,
- tool torque M = 800 Nm,
- impact piston weight 6.8 kg,
- speed of the impact piston at the moment of impact 11.5 m/s,
- ram stroke 60 mm (as an approximate value,
- speed at the moment of impact is of key importance).

4. Dynamic simulations

Based on the analysis of known design solutions of drilling machines, three concepts of an electric rotary-percussion drilling machine were developed. One of the concepts corresponds to the structure used in the Hilti TE MD20 drilling machine, hence, in the first stage, simulation tests of such a solution were carried out to verify the model and the parameters provided by the manufacturer. The design and parameters were determined based on available information [5]. After verifying the research methodology on this basis, model tests of an electric drilling machine were carried out for three different structures. The tests were conducted in the dynamic simulation module of Autodesk Inventor Professional.

The solutions developed and intended for simulation tests are the drilling machines, with the following characteristic components:

- a motor responsible for rotation and linear motor responsible for impact,
- a motor responsible for rotation and impact via a shaft with an inclined disc,
- a motor responsible for rotation and impact via the crankshaft.

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The parameters of the drilling machine were determined, and then, similarly to the Hilti drilling machine, various combinations of parameters were analysed. Additionally, motors of different power were tested to select the appropriate one. The initial simulations included the simplest air cushion model, and finally the Boyle-Mariotte law was used, which allowed for the determination of the nonlinear characteristics of the air cushion using the appropriate assumptions.

For each simulation, the path and speed of the impact piston, the rotational speed and torque of the electric motor, and the length and force of the spring that simulated the behaviour of the air cushion were plotted (Fig. 4). The key was to achieve the assumed impact frequency of 60 Hz and the required impact speed of 11.5 m/s at the moment of impact, which guaranteed achieving the calculated impact energy of 450 J.

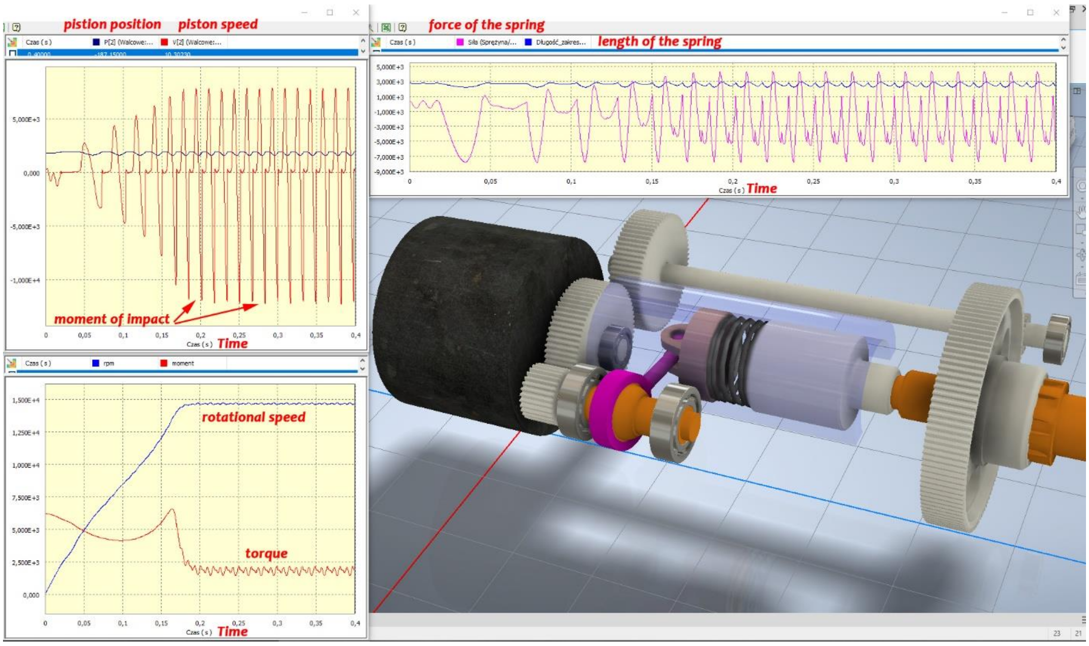

Fig. 4. An example screenshot from a dynamic simulation

4.1. Drilling machine with a linear motor

The first solution of the drilling machine was to use a rotating motor to generate rotational motion and a linear motor to generate impact. Taking into account the torque and rotational speed, an induction electric motor with a power of 22 kW and gears with a ratio of i = 5.8 were selected. The 22 kW motor itself weighs 172 kg. They were looking for a linear motor from different manufacturers. A SEW motor was selected, but the largest linear motor, SEW SL2P100ML, for an impact piston weight of 6.8 kg, allowed to generate a movement with a stroke of approximately 60 mm at a frequency of 9 Hz, which was too low. Moreover, for such a frequency, the impact piston does not achieve a speed of approximately 11.5 m/s, but only 1.7 m/s, which results in an impact energy of approximately 9.8 J. Hence, this solution was rejected.

4.2. Drilling machine with an inclined disk –asynchronous motor

Then, power requirement for an electric drilling machine with an inclined disc was checked. This solution assumed mounting the motor along the drilling machine, which allowed for impact and rotation without the need to use an angle gear. The gear ratios of the subsequent stages were selected to achieve a simultaneously impact frequency of f = 60 Hz and a tool rotation speed of approximately 250 rpm (Fig. 5).

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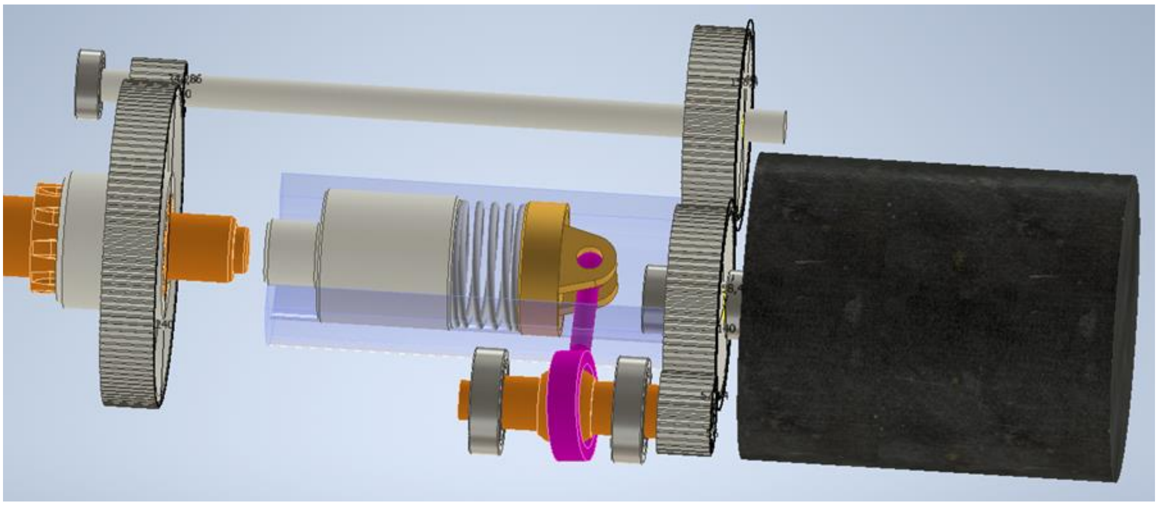

Fig. 5. 3D Model – electric percussion drilling machine with an inclined disk f = 60 Hz

For a 30 kW motor, in stable operation the torque demand was N = 145 Nm ÷ 216 Nm, and the motor operated in the speed range of 1461 rpm ÷ 1473 rpm, which is the operating point according to the catalogue of the selected motor. Hence, a 30 kW motor is sufficient in this solution (Fig. 6).

There are the following drilling machine parameters for a solution with an inclined disc and a 30 kW motor:

- multiplier from 1475 rpm to 3615.96 rpm – approx. I = 0.408 -> f = 60.25 Hz,
- reducer from 3615.96 rpm to 1466 rpm – approx. I = 2.466,
- reducer from 1466 rpm to 244 rpm – approx. I = 6,
- nominal tool rotation speed n = 244 rpm,
- torque from cutting N = 142 * 0.408 * 2.466 * 6 = 1171.13 Nm,
- impact frequency f = 60 Hz,
- impact piston weight 6.8 kg,
- maximum linear speed of the impact piston 12.7 m/s,
- computational impact energy: 548 J.

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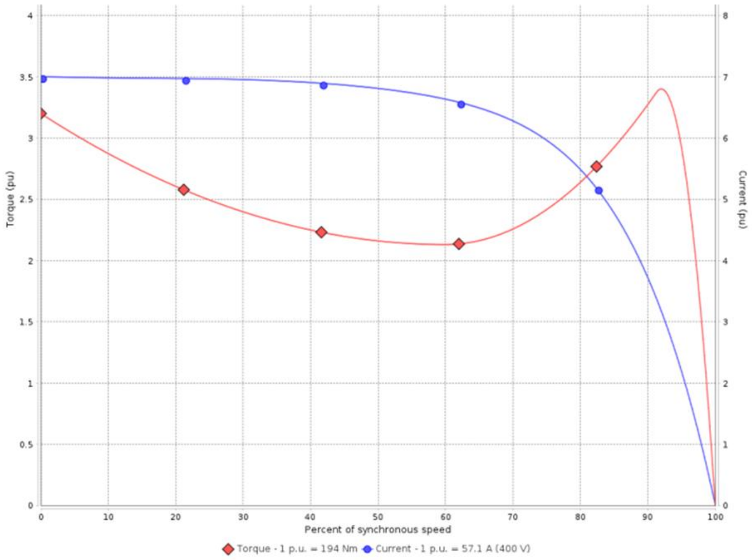

Performance	: 200/400/690/400 V 50 Hz 4P		
Rated current	: 114/57.1/33.1/57.1 A	Moment of inertia (J)	: 0.3743 kgm²
LRC	: 7.0	Duty cycle	: S1
Rated torque	: 194 Nm	Insulation class	: F
Locked rotor torque	: 320 %	Service factor	: 1.00
Breakdown torque	: 340 %	Temperature rise	: 80 K
Rated speed	: 1475 rpm	Design	: N

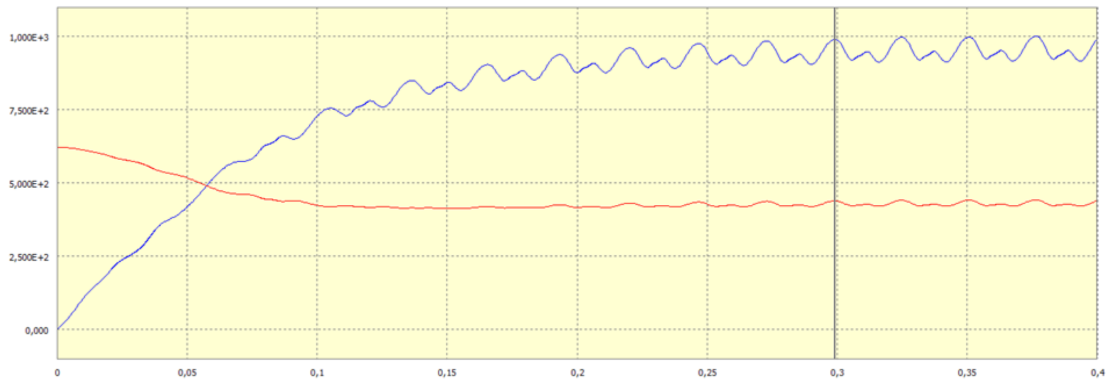

Fig. 6. Characteristics of 30 kW 200M/L motor and curves of speed and torque for a drilling machine with an inclined disk

The mechanism with an inclined disc is more complicated, what means that it may be too unreliable for the target drilling machine with high impact energy, that is why work on this solution was not continued.

4.3. Drilling machine with a crankshaft – asynchronous motor

The next analysed solution was a drilling machine with a crankshaft and, similarly to the Hilti drilling machine, mechanical gears. The model was developed to get the required parameters of the drilling machine. Thus, first the multiplier was used, then the reducing angular gear and the cylindrical reducer. For each analysed motor, its mechanical characteristics and rotor moment of inertia were taken into account (Fig. 7).

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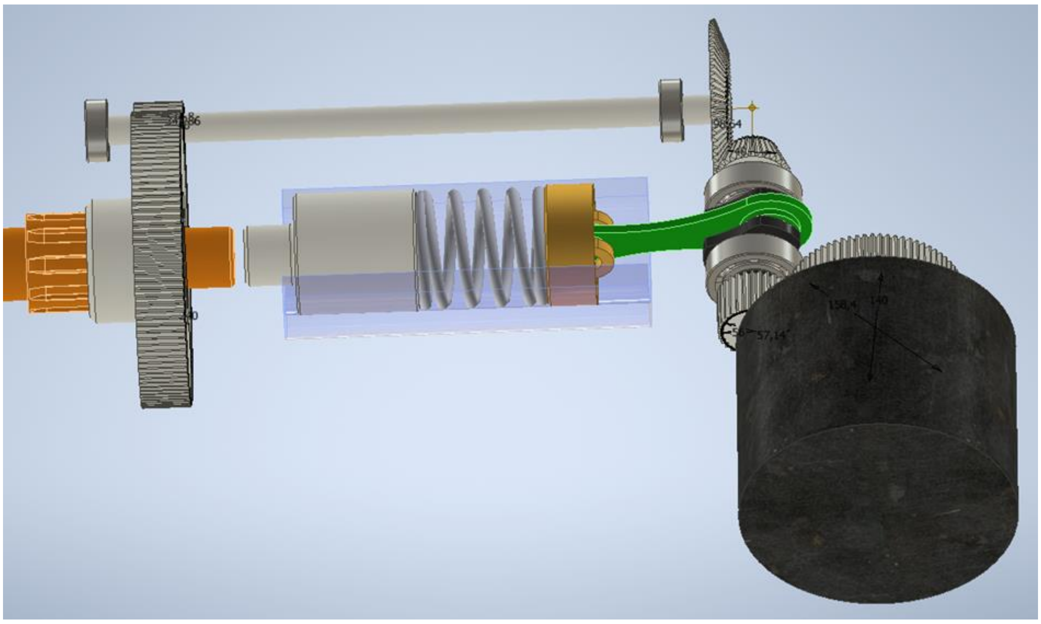

Fig. 7. 3D Model – electric percussion drilling machine with a crankshaft f = 60 Hz

Motors of different power were simulated. For a 30 kW motor (parameters as before), in stable operation the torque demand was N = 130 Nm ÷ 500 Nm, and the motor operated in the speed range of 1410 rpm ÷ 1475 rpm, which according to the catalogue, was a speed near the operating point. Thus, a 30 kW motor was insufficient for this solution. Only for the 45 kW 225M motor (P = 45 kW, N = 290 Nm, n = 1480 rpm, m = 341 kg) the satisfactory results were obtained. Several simulations were performed for various parameters. The selected data and information is presented below.

Drilling machine parameters for a solution with a crankshaft and a 45 kW motor (Fig. 8):

- multiplier from 1480 rpm to 3627.45 rpm – approx. i=0.408 -> f = 60.45 Hz,
- reducer from 3627.45 rpm to 1470.98 rpm – approx. i=2.466,
- reducer from 1470.98 rpm to 245.16 rpm – approx. i=6,
- nominal tool rotation speed n = 245 rpm,
- torque from cutting N = 290 * 0.408 * 2.466 * 6 = 1750.66 Nm,
- impact frequency f = 60 Hz,
- impact piston weight 6.8 kg,
- maximum linear speed of the beater 11.5 m/s,
- calculated impact energy: 450 J.

In steady operation, the torque demand was N = 247 Nm ÷ 268 Nm, and the motor operated in the speed range of 1450 rpm ÷ 1481 rpm, which is the operating point according to its catalogue. The dynamics of the torque change results from the motor characteristics. The selection of the elasticity coefficient and damping of the air cushion are crucial for the speed of the impact piston at the moment of impact, thus it was possible to reduce the piston stroke to 36 mm.

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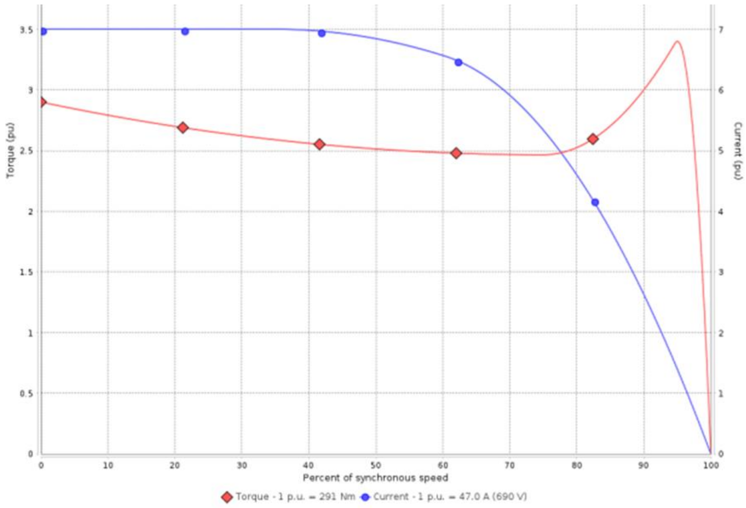

Performance	: 400/690 V 50 Hz 4P		
Rated current	: 81.1/47.0 A	Moment of inertia (J)	: 0.6143 kgm²
LRC	: 7.0	Duty cycle	: S1
Rated torque	: 291 Nm	Insulation class	: F
Locked rotor torque	: 290 %	Service factor	: 1.00
Breakdown torque	: 340 %	Temperature rise	: 80 K
Rated speed	: 1480 rpm	Design	: N

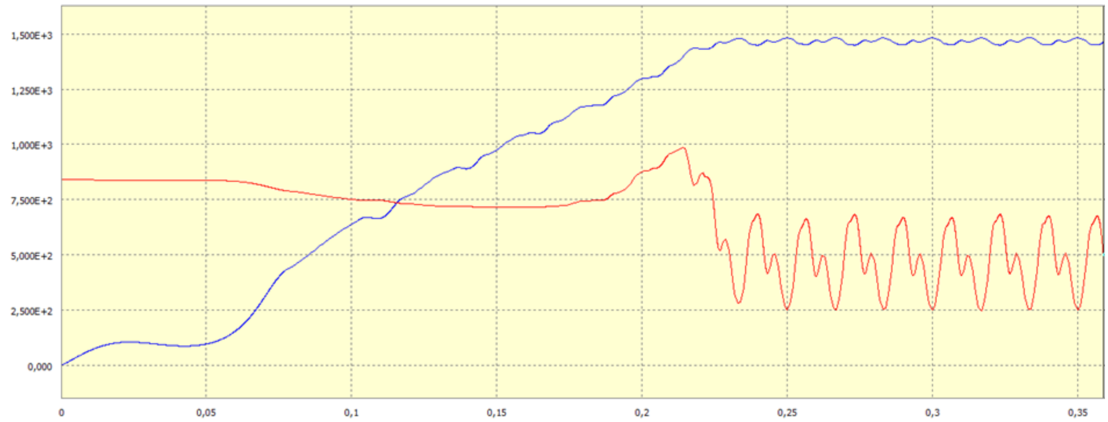

Fig. 8. Characteristics of the 45 kW 225M motor and the speed and torque waveforms for the crankshaft drill

4.4. Drilling machine with a crankshaft – motor with permanent magnets

In the next stage, the target drilling machine with a crankshaft was simulated, assuming the use of an electric motor with permanent magnets. According to the results of previous tests, the crankshaft drilling machine required a motor with a rated torque of 280 Nm. The simulations involved the use of a synchronous reluctance electric motor with permanent magnets from Nidec Leroy-Somer from the DYNEO+ series and Danfoss motors. The tests were carried out for motors with a rotation speed of approximately 1,500 rpm and approximately 3,000 rpm.

Several dozen simulations were performed for various motors and various parameters. The Danfoss EM-PMI300-T310-3200 motor had a power of 94 kW and a torque of 279 Nm at a speed of 3200 rpm and weighted 125 kg. For such a motor, it is possible to directly drive the impact mechanism through the motor, but then it is necessary to use a gear that reduces the revolutions from 3000 rpm to 250 rpm on the tool, so in total a gear or two gears must have a gear ratio of i = 12. Drilling machine operates at a rotation speed of approximately 3000 rpm after approximately 0.7 s. In steady-state operation, such a motor operates correctly already for a torque of approximately 95 Nm, thus use of a smaller motor

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may be considered. Use of permanent magnet motors, despite reduced weight and size, significantly improve the operating dynamics of the drilling machine. Induction motors, due to their very steep torque curve vs. speed characteristics, introduced torque fluctuations. However, the flat characteristics of permanent magnet synchronous motors make it easier to maintain constant torque at variable rotation speed.

5. Conclusions

As part of this research work many tests were conducted to determine possibility of designing an electric rotary-percussion drilling machine with parameters similar to drilling machines currently used on Face Master drilling jumbos. Known solutions for electric drilling machines were analysed. The solutions found in patents, mining models used historically and the solutions used in the construction industry were analysed. Currently, the authors know only one model of a mining electric rotary-percussion drilling machine - Hilti TE MD20. Then, several dozen dynamic simulations of various drilling machines solutions were carried out changing the parameters of the drilling machines and the electric motor.

Currently available linear motors do not allow designing the drilling machines with the expected parameters (especially impact energy and frequency). The solution with a shaft with an inclined disc, although used in the construction industry, is structurally complex, which will most likely not allow for long-term reliability. The crankshaft solution is known from mine electric drilling machines used several decades ago, it is used in drilling machines and construction hammers, and was used in the Hilti mining drilling machine, thus it was considered the most promising solution.

Requirements regarding the impact energy and frequency (450 J, 60 Hz), rotation speed and torque (250 rpm, 800 Nm) require the use of a 30 kW or 45 kW motor. Simulations were conducted for the most advantageous variant, ignoring the resistance to movement and friction, and only asynchronous motors were analysed. Structurally, such a drilling machine must have at least three single-stage gears, one of which is angular. Taking into account the relatively high power and the high degree of complexity of the design as well as the uncertainty of obtaining the required operating parameters of the drilling machine, it is recommended to work first on a solution with a power of several kilowatts. For the purposes of designing a new electric drilling machine, it is necessary to develop a stand for measuring the parameters of such drilling machines, especially for measuring the impact energy and frequency.

Simulations and analyses of drilling machines powered by synchronous motors with permanent magnets showed that this solution has a significant advantage over induction motors. Use of the permanent magnet motors significantly improves the operating dynamics of the drilling machine. Flat characteristics of permanent magnet synchronous motors make it easier to maintain constant torque at variable rotation speed. Danfoss motors selected for simulation can be successfully used from the point of view of torque demand. The best results gave Danfoss EM-PMI300-T310 motors in two versions: with a nominal speed of 1,600 rpm and a power of 59 kW and with a nominal speed of 3,200 rpm and a power of 94 kW. The 1600 rpm motor enables driving the drilling machine using a multiplier to obtain an impact frequency of 60 Hz. However, the 3200 rpm motor (controlled in such a way to obtain a rotation speed of 3000 rpm) enables direct driving the impact mechanism with a frequency of 60 Hz. It should be noted that both motors have higher torque than required. In particular, the 3200 rpm motor with a nominal torque of 279 Nm has a significant torque reserve, compared to the required 95 Nm during stable operation of a drilling machine. A drilling machine with a Danfoss EM-PMI300-T310 motor arranged longitudinally has dimensions similar to those of hydraulic drilling machines (Fig. 9), so the use of a smaller motor will be more advantageous in terms of weight and size.

The Danfoss motors have very high power and there is a need for their proper control and cooling. When using a higher speed motor, consider selecting a smaller motor, such as the EM-PME375-T150-2600, which has a nominal speed of 2,600 rpm but can operate up to 4,000 rpm. At a speed of 2,600 rpm, it generates a torque of 147 Nm with a power of 40 kW and it weighs 75 kg.

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Testing the electric drilling machine with a power of several kilowatts enables determining the real operating parameters and eliminate defects typical for the prototype, before designing the drilling machine for the drilling jumbos. Additionally, this solution will allow for verification and validation of digital models, what will facilitate designing the more powerful drilling machine.

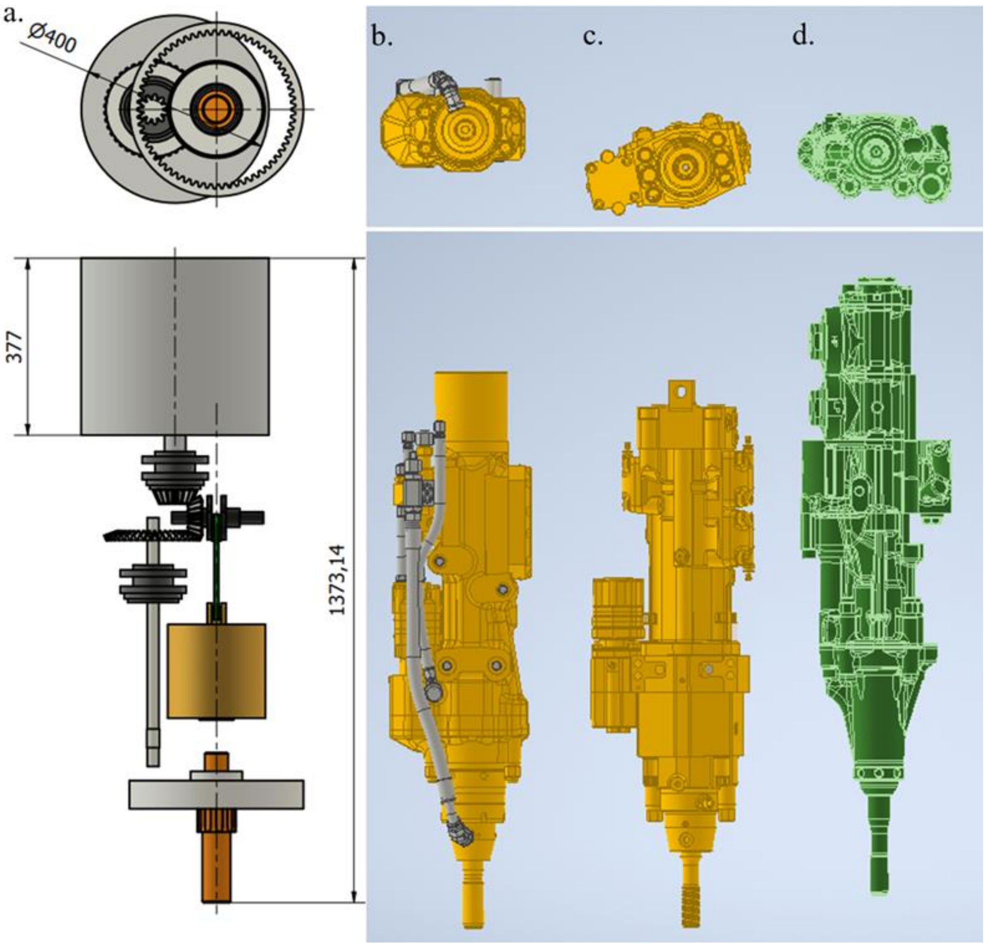

Fig. 9. Comparison of drilling machines:

a. electric with Danfoss EM-PMI300-T310 motor, b. hydraulic HC95, c. hydraulic MM20, d. hydraulic HC109

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