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Haulage drive with permanent magnet motors in longwall shearer – simulation model

Streszczenie. *Artykuł przedstawia wyniki przeprowadzonych symulacji pracy napędu posuwu kombajnu z zastosowanymi silnikami synchronicznymi, wzbudzanymi magnesami trwałymi. Przeprowadzono symulacje pracy dla trzech różnych napędów. Pierwszy stanowi odwzorowanie istniejącego napędu ze stosowanym obecnie silnikiem klatkowym. Drugi stanowiący propozycję zastąpienia silnika klatkowego silnikiem wzbudzanym magnesami trwałymi o zbliżonych parametrach do silnika obecnie stosowanego. Trzeci stanowi propozycję zastosowania w napędzie posuwu kombajnu silnika wzbudzanego magnesami trwałymi i gabarytach takich samych jak stosowany silnik klatkowy lecz o znacznie większej mocy oraz większym zakresie prędkości obrotowej. W tej części artykułu została przedstawione charakterystyki parametrów pracy modeli silników, które następnie zostały porównane.* ***Symulacja pracy napędu posuwu kombajnu z zastosowanymi silnikami synchronicznymi, wzbudzanymi magnesami trwałymi***

Abstract*. This paper presents results of simulation of longwall shearer haulage drive with permanent magnet synchronous motors. Simulation of operation has been conducted for three different drives. The first one represents currently used drive with cage induction motor. The second one uses permanent magnet motor as replacement of the cage induction motor, and parameters of new motor are similar to those of the old one. The third proposition is to exchange cage induction motor of the longwall shearer haulage drive for permanent magnet motor, with identical overall dimensions but with significantly increased rated power and rotational speed range. In this part of the paper the different motors' operational parameters and characteristics are presented and compared.*

Słowa kluczowe: napęd górniczy, silnik synchroniczny z magnesami trwałymi, kombajn górniczy, napęd elektryczny.
Keywords: mining drive, permanent magnet synchronous motor, longwall shearer, electric drive.

1. Introduction

The original header machine was used for the first time in 1870, when tunnel under the English Channel from Great Britain to France was driven [1]. The machine was haulaged by hydraulic means and excavated 2.4 km of the tunnel. The hydraulic haulage drives of the headers consisted of: electric motor, hydraulic pump, toothed gear and drive wheel.

This type of design had to include a large quantity of inflammable oil, and the control circuit of the haulage speed and tractive force was complex. The hydraulic systems made it difficult or even impossible to automate header operation, and they were characterized by low efficiency.

With the development and modernization of mining machines the haulage drive system described above was replaced with the system containing dc electric motor, and this simplified the drive a great deal. In the strictly electrical design the motor drives directly the toothed gear.

In the subsequent phase of developing header haulage drives, the ac motors were introduced, supplied via frequency converters. This solution is still used nowadays.

Since the progress in the field of electric drives is enormous, these drives develop better and better parameters as far as efficiency, power density and control accuracy are concerned. In our opinion, the next phase in the development of electric mining drives will be aimed at introducing and implementing on a large scale mining motors excited with permanent magnets. The research and design work, which are at present conducted in the Instytut Napędów i Maszyn Elektrycznych KOMEL and Instytut Techniki Górniczej, with support and cooperation of DAMEL company, aim at elaboration of new generation of haulage drives for header machines. These drives will be equipped with permanent magnet synchronous motors.

The rotating machines excited with permanent magnets are widely used in many different branches of industry, for different applications, from personal computer drives to traction drives (railways, electric cars) and high power generators for the wind power farms.

Due to different advantages displayed by PM machines their fields of application continuously expand and this fosters growing interest and development of drives using these motors.

The mining industry is characterized by difficult operating conditions of the underground machine drives. Apart from the necessity of ensuring safety of the work crews in the surroundings which pose explosion hazards (methane, coal dust), the mining motors are often exposed to high levels of vibrations, increased ambient temperatures, dust laden atmosphere, sudden load changes, mechanical damage. For these reasons, introducing new designs which are already popular and verified in other branches of industry is difficult, since new and innovative solutions must meet very tough operating conditions and be characterized by very high reliability.

Previous implementation of permanent magnet motors in the mining drives proves that such motors may well be up to the job, while their operational parameters are much better than those of currently used cage induction motors [2].

2. Advantages of permanent magnet motors

The idea of using permanent magnet motors in the mine industry is well supported by the increasing demands which have to be met by the drive manufacturers. These requirements relate to operational parameters, energy consumption and efficiency, safety, decreased dimensions and control accuracy.

Application of motors excited with permanent magnets will provide a series of attractive opportunities which might indicate new directions for development of mining techniques. Use of PM motors may generate the following advantages (among others):

1. Smaller overall dimensions of motors will help to design more compact devices, while lower motor weight will lead to reduction in total device weight.
2. Higher efficiency of synchronous motors with permanent magnets in relation to cage asynchronous motors which are currently and commonly used in mining industry, will facilitate reduction of energy consumption (mining drives will attain better energy-consuming parameters).
3. Better dynamic properties of motors with permanent magnets will facilitate the use of more precise algorithms of speed control and accurate positioning.

4. Higher efficiency of synchronous motors with permanent magnets is obtained by elimination of losses present in induction machine rotor by removing rotor winding and exchanging it for permanent magnets.
5. Higher torque overload capacity of permanent magnet motors makes it possible to exchange them for oversized induction motors used nowadays. At present, oversized motors are used, with higher rated power and higher shaft height, on account of required maximum torque. In case of permanent magnet motor, the required maximum torque may be obtained using motor with lower rated power and with smaller overall dimensions.

Synchronous motors excited with permanent magnets (abbr. PMSM - *Permanent Magnet Synchronous Motor*) dedicated to mining applications do not differ greatly from standard cage induction motors, except for the rotor design. The design, depending on motor's final place of assembly, must take into account necessity of built-in or added encoder and the way of accessing its output wires. Encoder is a transducer used for quantitative measuring of rotational or linear motion and transforming it into a series of electrical impulses. In synchronous motors excited with permanent magnets, an encoder is indispensable for motor control.

3. Elaborated motor model for longwall shearer KSW-460NE

The elaborated motor models should be eventually applied in the haulage drive of KSW-460NE longwall shearer (weight 32 t). This shearer is equipped with two working (cutting) elements, driven with motors rated at 200 kW. The movement of the shearer along the wall is achieved with two electric tractors of the haulage drive; each tractor is driven with cage asynchronous motor dSKK(s) 180L4z rated at 45 kW.

In the design stage of the work, we have elaborated models of two motors excited with permanent magnets. These models should demonstrate different strategies which might be achieved in modernized haulage drive operation.

The first strategy involves modification of the longwall shearer haulage drives by exchanging existing motors for motors with smaller overall dimensions and weight, but similar operational parameters. Since the PM motors are able to obtain higher energy density (energy per volume of active part of the motor), it is possible to design a motor, which will attain parameters similar to those of cage induction motors (used currently in the shearer's haulage drive) and will be smaller.

The justification of decreasing overall motor dimensions (its shaft height, length) will be seen directly in decreased drive size and shearer dimensions. Such a modification may be attractive to the manufacturers of mining machines, since it may be applied in the shearer dedicated for operation in extra thin coal seams. Such motors might also be applied in similar drives such as automated longwall system Mikrus produced by KOPEX.

The other proposed drive modification strategy starts with the assumption where overall motor dimensions remain unchanged (in relation to currently used cage induction motor), but operational parameters are improved as well as the range of speed corresponding to rated torque. In this case we may discuss increase in rated and maximum torque, which may lead directly to higher effective attainable haulage speed of the shearer working (mining) the longwall. In both cases, i.e. increasing motor's power or decreasing motor's overall dimensions (and maintaining motor's parameters at the level of currently used induction motor), the efficiency of motor excited with permanent magnets should be at least by several per cent higher than efficiency of cage induction motor.

Within the framework of the project, we have conducted calculations of electromagnetic circuits of the motors: with decreased overall motor dimensions (**KOMEL1**) and with maintained original motor dimensions and increased power (**KOMEL2**).
During the research we have elaborated two types of synchronous motors with permanent magnets:

KOMEL1 - PMSM motor with lower motor shaft height (H180)

KOMEL2 - PMSM motor with unchanged motor shaft height (H160)

4. Model of KOMEL1 motor – reduced dimensions

The first elaborated motor model is a PMSM motor with reduced shaft height and reduced active core length, from original L_{Fe}=265 mm to L_{Fe} =185 mm. The calculated rated parameters of the motor are set out in Table 1 and compared to parameters of dSKK(s) 180L4z motor.

Table. 1. Comparison of parameters of commonly used motor with parameters of model PMSM motor KOMEL1.

Manufacturer, type	dSKK(s) 180L4z	KOMEL1
Shaft height	180	160
Rated power P_N	45 kW	54 kW
Rated rotational speed n_N	1459 rpm	1700 rpm
Rated voltage U_N	440 V	440 V
Rated current I_N	74 A	77 A
Efficiency η	90 %	95 %
Rated torque T_N	295 N·m	304 N·m
Maximum rotational speed	3500 rpm	4000 rpm

On the basis of KOMEL1 motor calculated parameters we may draw the conclusion that this motor, using the proposed electromagnetic circuit, will provide rated power and torque higher by 16% even though its dimensions are reduced and its shaft height is one level down in motor's series of types (from 180 mm down to 160 mm). Likewise, the calculated efficiency at the rated speed of 1700 rpm is *c*. 5% higher in the PM motor.

Application of the PMSM motor proposed by the authors should enable operation of the haulage drive with rated torque in the speed range from 0 to 1700 rpm.
The calculated operational characteristics for KOMEL1 motor are shown in Fig.1 for different supply modes:

with rated current I_N = 77 A

with current 2 x I_N = 154 A

Two speed regions may be observed within the torque-speed curves. In the first region, when motor is supplied with rated current, the motor maintains constant torque while speed increases from 0 to 1700 rpm. In the second zone, the motor operates with weakened main magnetic flux [7], which makes it possible to increase haulage speeds at the expense of gradual torque decrease. The impact of weakening flux on power vs. speed characteristics $P = f(n)$ is shown in Fig.2.

In induction motor drive the rated torque was kept until the speed attained 1459 rpm. In the second speed control region the PMSM motor operates with constant power at shaft (rough approximation).

Both motors (dSKK(s) 180L4z and KOMEL1) are water cooled (external cooling). Reduction of motor dimensions should facilitate assembly of the cooling system.

The presented model of PMSM motor KOMEL1 is an example showing how to reduce assembly dimensions of the motor while maintaining or improving its rated parameters

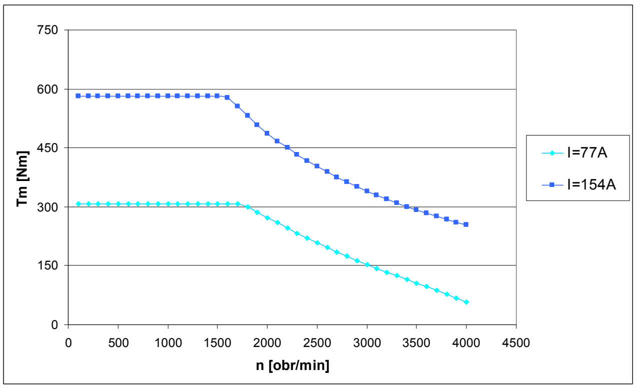

Fig. 1. Calculated curves of mechanical torque T_m vs. rotational speed n - motor model KOMEL1.

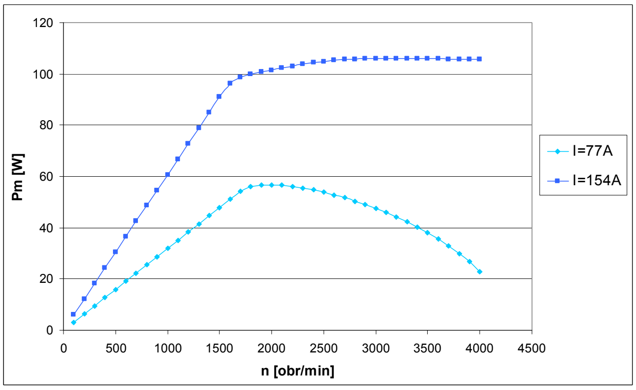

Fig. 2. Calculated characteristics of the output power - motor model KOMEL1.

5. Model of KOMEL2 motor – dimensions same as in dSKK(s) 180L4z motor

The second elaborated PMSM motor model is the one provisionally called KOMEL2. In this variant the electromagnetic circuit has been worked out in such a way that motor's dimensions and method of assembly in the longwall shearer and connection to a supply source should be the same as in standard motor dSKK(s) 180L4z. Rated parameters of motors KOMEL 2 and dSKK are set out in Table 2.

Table 2. Comparison of parameters of commonly used motor with parameters of model motor KOMEL 2.

Type	dSKK(s) 180L4z	KOMEL2
Shaft height	180	180
Rated power P_N	45 kW	70 kW
Rated rotational speed n_N	1459 rpm	2250 rpm
Rated voltage U_N	440 V	440 V
Rated current I_N	74 A	100 A
Efficiency η	90 %	96 %
Rated torque M_N	295 N·m	298 N·m
Maximum rotational speed	3500 rpm	4000 rpm

PMSM motor, variant KOMEL2, has been designed in such a way that its rated torque at shaft is practically unchanged (*c.* 300 N·m - Table 2). The rated rotational speed has been increased from 1459 to 2250 rpm, so that with torque essentially unchanged the rated power is increased up to 70 kW, which is equal to 155% of dSKK(s) 180L4z motor's rated power.

Motor characteristics of KOMEL2 motor variant for the following supply modes are depicted in Fig.3 and Fig.4:

at rated current I_N = 98 A

at current 2 x I_N = 196 A

In case of KOMEL2 motor the overall dimensions have not been changed and remained the same as in dSKK(s) 180L4z motor, even though the length of electromagnetic core has been reduced from L_{Fe}=265 mm to L_{Fe}=200 mm. Lack of change in dimension is caused by the fact that control of PM motor requires an encoder, which is usually fitted to the motor shaft, which in turn increases the length of the said shaft. For KOMEL2 motor, the encoder and length of electromagnetic core have been chosen so that total length of the motor remains the same as in dSKK(s) 180L4z motor.

The encoder is assembled inside the motor casing, in a separate encoder box which protects the device from possible mechanical and thermal damage. A similar solution has been used in motors driving the GAD-1 tractor manufactured by KOMEL [2, 3].

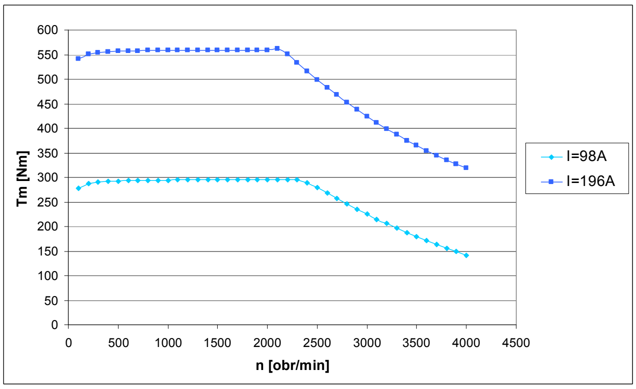

Fig. 3. Calculated mechanical torque characteristics - motor model KOMEL2.

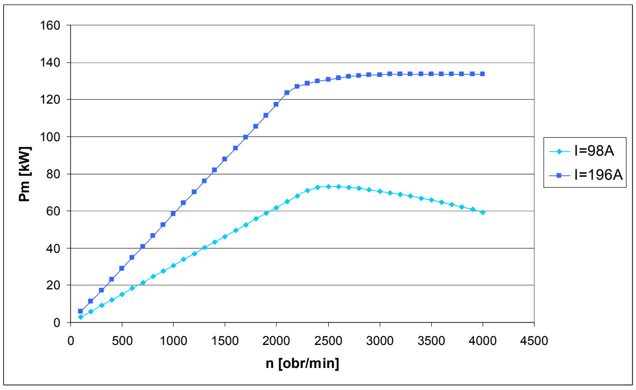

Fig. 4. Calculated characteristics of the output power - motor model KOMEL2.

6. Simulation of shearer operation for working speed equal to *v* = 10 m/min.

Computer simulations aimed at determining the drive characteristics of dSKK(s) 180L4z motor and proposed PMSM motor KOMEL1 have been run with the help of PSIM software. The PMSM motor characteristics are shown in Fig.5. They have been subsequently used for simulation of motor operation in shearer drive. In the first speed regulation region, called usually the constant-torque region, the motor's voltage (RMS value) increases at the rate 256 V/1000 rpm and attains 439 V at the base speed of 1675 rpm. The mechanical power output by the motor model increases at the rate 31.9 kW/1000 rpm and attains 54.3 kW at the base speed. The motor model current (RMS value) remains almost constant in the first speed region, increasing slightly from 75.1 A to 77 A at base speed.

In the second speed regulation region, called usually the constant-power region, the supply voltage of the motor model (RMS value) is constant and equal to 429 V. The mechanical power generated by motor model is constant and equal to 54.3 kW. In order to conduct simulations this power has been artificially kept constant by supplying the motor with increasing current in the second speed region.

The model motor current increases steadily reaching 103.5 A at 4000 rpm.

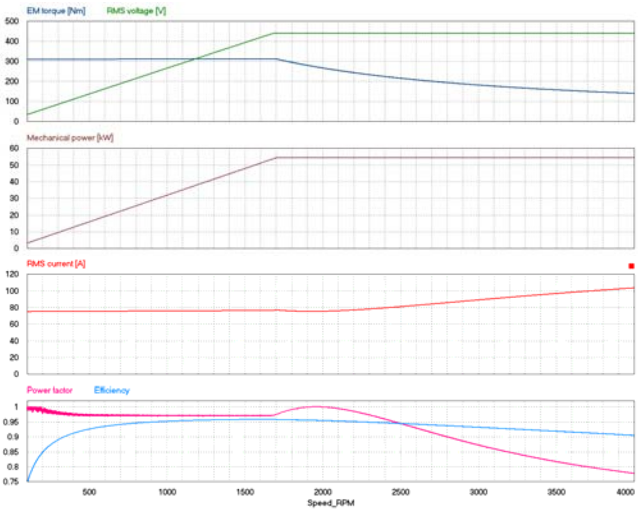

Fig. 5 Characteristics of motor model KOMEL1 (54 kW) used for simulations of drive operation.

The load characteristics are shown in the subsequent figure 6 and 7. They have been used in simulations of operation of shearer's haulage drive.

Since measurements of KSW-460NE shearer haulage drive load courses are not available, they will be determined using measurements taken from the haulage drive of KSW-750E shearer [9,10]. The approximate loading of KSW-460NE shearer drive will then be calculated by analogy.

Drive wheel with involute profile of KSW-750E shearer is equipped with 12 teeth. The drive wheel of KSW-460NE shearer has 9 teeth. On account of smaller number of teeth, the modulation of the tractive force will be more extensive in KSW-460NE shearer and hence the regulation range of the motor shaft torque in the haulage drive will also be wider.

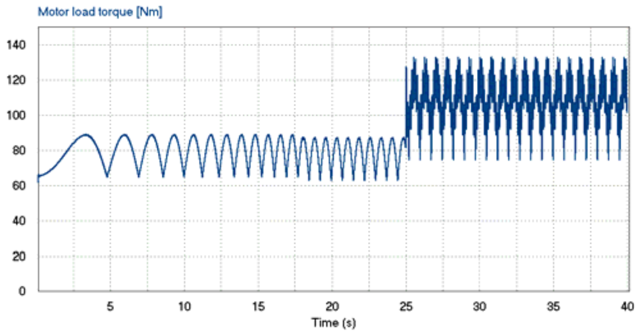

Fig. 6 Loading torque for haulage drive motor with haulage speed increasing to 10 m/min.

The loading of motor in the tractor drive of the shearer is shown below.

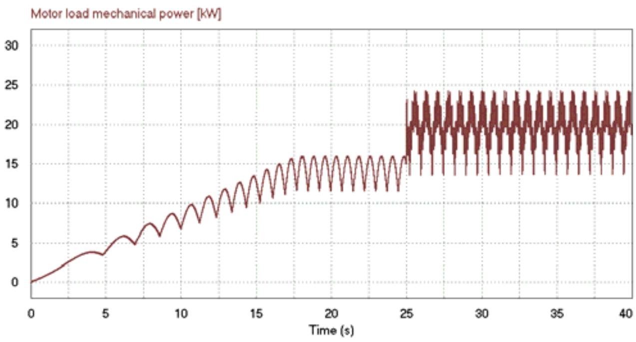

Fig. 7 Load power for haulage drive motor with haulage speed increasing to 10 m/min.

Simulations of the haulage drive operation of the longwall shearer have been conducted for the calculated characteristics of the motor model (Fig.5) and load characteristics. The simulations for both motors have assumed the working speed of the shearer to be equal to v = 10m/min. The waveforms of rotational speed and torque are shown in Fig.8.

a)

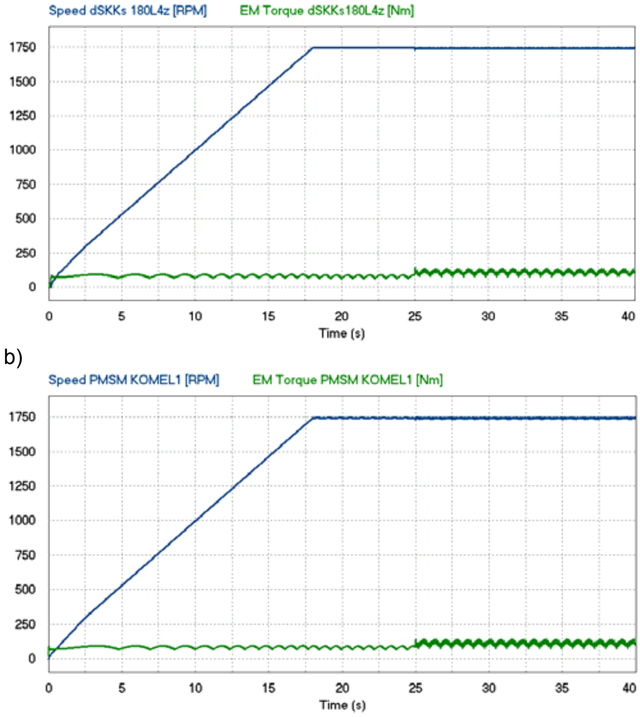

Fig. 8. The waveforms of rotational speed and electromagnetic torque of the haulage drive with haulage speed increasing to 10m/min; a) for modelled motor dSKK(s) 180L4z; b) for modelled motor KOMEL1.

When the charts are compared, we may observe that rotational speed stabilizes at 297 rpm in the 18th second of the operation for both motors. In the interval between 18th and 25th second (manoeuvring work), the average value of the rotational speed of standard motor attains 1747 rpm and is approximately equal to PMSM motor speed (1744 rpm). The actual working (mining) of the longwall shearer is started in the 25th second of drive operation, and this corresponds to increase in load torque.

We may observe (Fig.9) that for the time interval simulating manoeuvring of the shearer (between 18th and 25th second of operation), the average value of motor's mechanical power is equal to 14.4 kW. The average electrical power drawn by the induction motor over the same time interval is equal to 17.2 kW, while in case of PMSM motor it is equal to 15.72 kW.

During working (mining) of the longwall (time interval from 25 to 40 s) with stable rotational speed, the induction motor is loaded with average power equal to 19.8 kW and the same holds for PMSM motor. The power drawn by standard motor is equal to 22.8 kW, while the PMSM motor power input is equal to 21.22 kW. Simulated efficiency and power factor waveforms for both motors are shown in Fig.10.

On the basis of Fig.10 we may conclude that PMSM motor attains higher power factor over the whole operational range. During manoeuvring the power factor of PM motor is equal to 0.997, while the standard motor dSKK(s) 180L4z operates at power factor equal to 0.65.

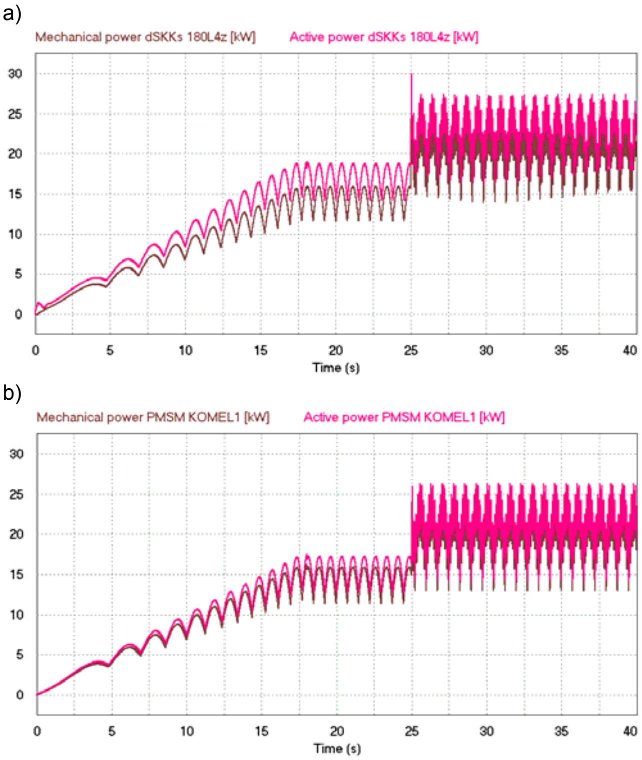

Fig. 9. The waveforms of output mechanical power and input electrical power of the haulage drive motor with haulage speed increasing to 10m/min; a) for modelled motor dSKK(s) 180L4z; b) for modelled motor KOMEL1.

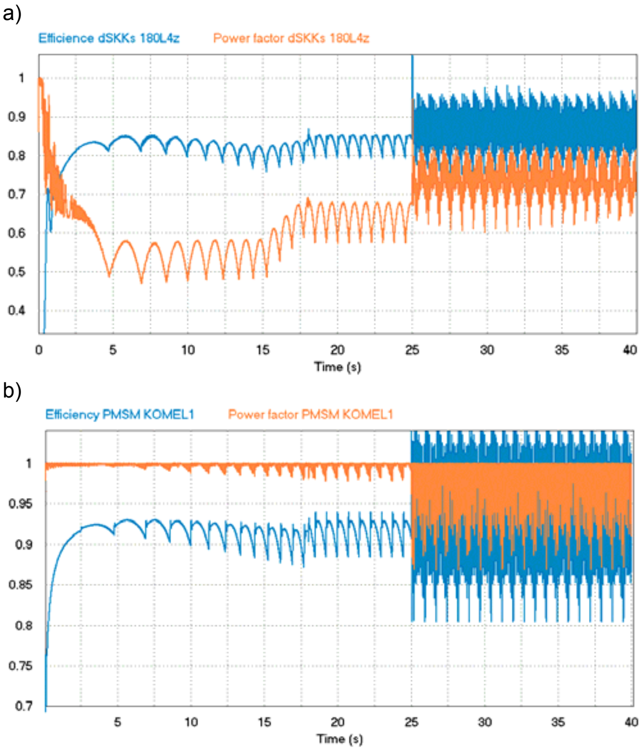

Fig. 10. Courses of power factor and efficiency of haulage drive motor for haulage speed increasing to 10m/min; a) for modelled motor dSKK(s) 180L4z; b) for modelled motor KOMEL1.

During working (mining) the longwall with the set speed, the PM motor attains the average power factor of 0.98, while the standard motor operates at power factor equal to 0.74.

Conclusions

The calculated parameters enabling comparison of motors' operational parameters under simulated operational conditions are set out in Table 3.

Table 3. Calculated operational parameters of the original motor and motor excited with permanent magnets.

Type of drive motor	Squirrel cage induction motor dSKK(s) 180L4z		Synchronous motor with permanent magnets type IPMSM	
Operating conditions / Parameters	Manoeuvring at a speed of 10 m/min	Mining at a speed of 10 m/min	Manoeuvring at a speed of 10 m/min	Mining at a speed of 10 m/min
Mechanical output power	14.44 kW	19.8 kW	14.42 kW	19.83 kW
Taken electric power	17.23 kW	22.77kW	15.72 kW	21.22 kW
Power factor	0.646	0.736	0.997	0.984
Efficiency	83.8 %	87 %	91.7 %	93.4 %
Motor current (RMS)	34.92 A	40.48 A	22.52 A	30.05 A
Network current via frequency converter (RMS)	36.76 A	42.61 A	21.72 A	29.38 A

On the basis of these parameters and for different modes of drive operation we may draw the conclusion that PMSM motor is characterized by higher efficiency both during manoeuvring at set speed (by 8%) and during working (mining) the longwall (by 6.4%). The power factor is also significantly higher for both modes of operation.

It must be emphasized that PMSM motor has been elaborated for motor shaft height equal to 160 mm, while its core length is shorter by 80 mm.

For the coal getting speed of the shearer equal to v = 10 m/min, KOMEL1 motor exhibits lots of advantages as to the attained parameters.

It must be noted that the longwall shearer usually works with several duty cycles, at different speeds, where the motors operate at different loads. What is more, load of shearer drive will vary in accordance with longwall gradient and the shearer path.

The maximum possible incline angle for the shearer traction is 35°. The required rotational torque of the haulage drive motor for this incline causes a decrease in the operational speed of dSKK(s) 180L4z motor. Since for KOMEL2 motor the speed range, where the motor torque attains rated value is very wide in comparison to dSKK(s) 180L4z and KOMEL1 motors, this should allow for the shearer drive operation with higher rotational speed at higher haulage speeds than in case of shearer equipped with standard dSKK(s) 180L4z motors.

In the next part of this publication we shall present results of simulations of KOMEL1 and KOMEL2 motors for shearer working (mining) at speeds equal to v = 5 m/min. and v = 20 m/min. for both horizontal and inclined track of the shearer (incline gradient 35°).

In addition, we shall conduct economic analysis of the operation of all compared motors for three different haulage speeds.

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