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Haulage drive with permanent magnet motors in longwall shearer – simulation of operation

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 ramach porównania parametrów pracy wszystkich napędów została wykonana i przedstawiona analiza ekonomiczna dla różnych warunków pracy kombajnu.* ***Wyniki symulacji pracy napędu posuwu kombajnu z zastosowanymi silnikami synchronicznymi, wzbudzanymi magnesami trwałymi***

Abstract*. This paper presents the results of simulations of the haulage drive of longwall shearer machine. The drive uses permanent magnet synchronous motors. Simulations have been performed for three different drives. The first model represents currently used drive with squirrel-cage motors. 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 significantly increased rated power and rotational speed range. In this paper we have compared operational parameters of all three drives and economic analysis has been conducted for different operating conditions of the header machine.*

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

In the first part of paper we have presented two models of synchronous machines excited with permanent magnets (abbr. PMSM - Permanent Magnet Synchronous Motor). We propose to replace dSKK(s) 180L4z induction motor currently used in the haulage drive of the KSW-460NE longwall shearer with either of the motors. The models denoted as KOMEL1 and KOMEL2 stand for two different conceptions of haulage drive modernization. KOMEL1 motor retains operational parameters approximately equal to those of the original induction motor, while its dimensions are less (length, diameter, weight). KOMEL2 motor retains original overall dimensions of dSKK(s) 180L4z motor, but due to distinctive properties of PMSM motors, operational parameters such as rated power, torque overload capacity and efficiency will be improved. The calculated rated parameters of both PMSM motors are presennted in Table 1 and compared with parameters of dSKK(s) 180L4z motor.

Table 1. Comparison of rated parameters of dSKK(s) 180L4z motor and two variants of proposed PMSM motors

Manufacturer and type	CELMA INDUKTA dSKK(s) 180L4z	KOMEL1	KOMEL2
Mechanical shaft size	180	160	180
Rated power P_N [kW]	45	54	70
Rated rotational speed n_N [rpm]	1459	1700	2250
Rated voltage U_N [V]	440	440	440
Rated current I_N [A]	74	77	100
Efficiency η [%]	90	95	96
Rated torque T_N [N·m]	295	304	298
Maximum rotational speed [rpm]	3500	4000	4000

In the first part of the paper we have demonstrated and compared time courses of selected electrical and mechanical quantities characterizing the operation of electric motors (power at shaft, power input, electromagnetic torque, rotational speed, power factor, efficiency), obtained by computer simulations. For simulation purposes, we have assumed linear speed of the KSW-460NE haulage drive to be equal to 10 m/min (working, i.e. cutting speed), for two different drive motors: induction motor dSKK(s)180L4z and PMSM motor, variant KOMEL1.

Nowadays the manufacturers of longwall header machines declare wide ranges of the haulage speed. Depending on the haulage drive load torque, which results from the operation of tractive system, resistance due to coal cutting processes and angle of longitudinal incline of the heading, the mining speed attainable for given operational conditions varies. That is why in the present paper we have shown (in the tabular form) and described the results of computer simulations for the selected operating conditions (three different haulage speeds) of the haulage drive of KSW-460NE longwall shearer.

The diverse parameters of the mined longwall make it difficult to assess beforehand the haulage speed of the shearer. While simulating operation of KSW-460NE shearer, we have run calculations for the average haulage speed of 10 m/min; however, we have also decided to analyze drive operation at speeds judged by the authors to be extreme: 5 m/min (slow speed) and 20 m/min (fast speed, maximum haulage speed offered by the manufacturer). We have simulated operation of the haulage drive at these speeds for working conditions (i.e. mining the longwall) as well as for idle-run conditions (manoeuvring work).

The other issue discussed in the second part of the paper is energy performance/effectiveness of the new PMSM motors in the haulage drive. For each analyzed operational mode of the shearer, we have investigated the impact of using PMSM motors (variants KOMEL1 and KOMEL2) in haulage drive in relation to standard dSKK(s)180L4z motor. The following problems have been analyzed:

- energy consumption (energy drawn from the supply network);
- network load current (RMS);
- thermal power dissipated in the haulage drive motor.

The computer simulations presented in the current paper have been conducted in the same way as simulations presented in the first part of the paper, i.e. assuming and calculating load characteristics of the drive in accordance with reference [1] and on the basis of calculated electromechanical characteristics of the proposed PMSM motors (variants KOMEL1 and KOMEL2).

2. Analysis of the longwall shearer KSW-460NE PM motors' drive operation.

In order to compare electrical and mechanical parameters attained by the longwall shearer haulage drive depending on the type of electric motor used, we have run series of simulations. Haulage motor drives presented in Table 1 have been modelled in using PSIM software [2]. The motors have been mechanically loaded in accordance with two different driving modes: manoeuvring and working with a horizontally situated longwall. For each operating mode three different haulage speeds have been considered: 5, 10 and 20 m/min. When simulation models of the haulage drive equipped with different motors have been worked out, we have assumed that for a given mode of operation and at a set haulage speed the mechanical load is identical in each case, i.e. mechanical power at shaft of both motors is identical. Simulation models of motors have taken into account the power electronics supply sources: for induction motor dSKK(s)180L4z frequency converter with scalar voltage inverter, and for PMSM motors (two variants: KOMEL1 and KOMEL2) frequency converter with vector voltage inverter and active rectifier.

Table 2. Selected parameters of the haulage drive in longwall shearer KSW-460NE (during manoeuvring and working with a horizontally situated longwall), depending on type of electric motors used in the drive

Type of drive motor	Asynchronous cage motor, rated at 45 kW, type dSKK(s)180L4z		PMSM - KOMEL1, rated at 54 kW		PMSM – KOMEL2, rated at 70 kW	
Mode of operation during measurements / Parameters	Manoeuvring at 5 m/min.	Working the longwall at 5 m/min.	Manoeuvring at 5 m/min.	Working the longwall at 5 m/min.	Manoeuvring at 5 m/min.	Working the longwall at 5 m/min.
Motor's output power (mechanical)	7.26 kW	9.92 kW	7.24 kW	9.91 kW	7.24 kW	9.91 kW
Motor's input power (electrical)	8.54 kW	11.33 kW	7.74 kW	10.49 kW	7.68 kW	10.42 kW
Motor's power factor	0.53	0.633	0.998	0.984	0.998	0.982
Motor's efficiency	85 %	87.6 %	93.5 %	94.5 %	94.3 %	95.1 %
Motor's current (RMS)	35.96 A	39.84 A	22 A	29.43 A	28.18 A	37.71 A
Network current (RMS)	22.26 A	24.66 A	10.22 A	13.86 A	10.15 A	13.77 A
Mode of operation during measurements / Parameters	Manoeuvring at 10 m/min.	Working the longwall at 10 m/min.	Manoeuvring at 10 m/min.	Working the longwall at 10 m/min.	Manoeuvring at 10 m/min.	Working the longwall at 10 m/min.
Motor's output power (mechanical)	14.44 kW	19.8 kW	14.42 kW	19.83 kW	14.42 kW	19.82 kW
Motor's input power (electrical)	17.23 kW	22.77 kW	15.72 kW	21.22 kW	15.56 kW	21.04 kW
Motor's power factor	0.646	0.736	0.997	0.984	0.997	0.982
Motor's efficiency	83.8 %	87 %	91.7 %	93.4 %	92.7 %	94.2 %
Motor's current (RMS)	34.92 A	40.48 A	22.52 A	30.05 A	28.71 A	38.35 A
Network current (RMS)	36.76 A	42.61 A	20.77 A	28.03 A	20.56 A	27.79 A
Mode of operation during measurements / Parameters	Manoeuvring at 20 m/min.	Working the longwall at 20 m/min.	Manoeuvring at 20 m/min.	Working the longwall at 20 m/min.	Manoeuvring at 20 m/min.	Working the longwall at 20 m/min.
Motor's output power (mechanical)	28.86 kW	39.65 kW	28.7 kW	39.66 kW	28.69 kW	39.65 kW
Motor's input power (electrical)	32.46 kW	44.08 kW	33 kW	44.17 kW	32.21 kW	43.29 kW
Motor's power factor	0.904	0.904	0.539	0.671	0.585	0.705
Motor's efficiency	88.9 %	90 %	87 %	89.8 %	89.1 %	91.6 %
Motor's current (RMS)	47.41 A	64.03 A	80.42 A	84.4 A	72.49 A	80.94 A
Network current (RMS)	49.58 A	67.37 A	43.59 A	58.36 A	42.55 A	57.2 A

Selected electrical and mechanical parameters of haulage drive of longwall shearer KSW-460NE, obtained by simulations described above, are set out in Table 2 for two modes of operation (manoeuvring and working with a horizontally situated longwall), three different haulage speeds and two different motors. Parameters given in Table 2 relate to a single tractor.

From the data set out in Table 2 it may be observed that independently of the fact whether the shearer is manoeuvring or working the wall and regardless of the haulage speed, the drive equipped with PMSM motor, variant KOMEL2 (70 kW) draws less power from the supply network than currently used induction motor dSKK(s) 180L4z.

If PMSM motor KOMEL1 (54 kW) is used in the tractor drive, the situation is similar with the exception of operation at haulage speed equal to 20 m/min (then active power drawn by the PMSM motor is slightly larger than in case of the induction motor). The haulage speed 20 m/min is applied only during manoeuvring; when the wall is worked (mined) the speed does not usually exceed 7 ÷ 10 m/min. In this paper we investigate haulage speed equal to 20 m/min theoretically only. The decrease in active power supplied to PMSM motors is caused by higher efficiency of such motors, which - among other features - do not possess a rotor winding and hence the rotor power losses are practically absent [3].

On the basis of Table 2 data it may also be noted that for haulage speeds equalling 5 and 10m/min the power factor $\cos\varphi$ is much higher for PMSM motor than for the cage induction motor. For instance, in manoeuvring mode and at speed equal to 5m/min, the power factor $\cos\varphi$ for induction motor is 0.53, while in identical conditions the power factor $\cos\varphi$ for PMSM motor is 0.998.

Small value of power factor for induction motor operating in the low range of rotational speeds is due to the specific motor control method. Up to the rated speed the motor is controlled in accordance with algorithm U/f = const, so that magnetic flux induced by the reactive component of the supply current is maintained at a constant value. When rotor rotational speeds are low, the participation of the so-called magnetizing current in the supply current of induction motor is significant, and this causes considerable decrease in the power factor. In PMSM motor, until a given rotational speed is attained (the so-called base speed), the magnetic flux is generated mostly by permanent magnets, so that the reactive component of the supply current is relatively low and the power factor is high.

For the maximum shearer's haulage speed (20m/min) the more favourable power factor $\cos\varphi$ is exhibited by the induction motor. For instance, during manoeuvring the power factor for PMSM motor, variant KOMEL1 (54 kW) is 0.539 and for variant KOMEL2 (70 kW) it is 0.585, while under identical conditions power factor for induction motor is 0.904. Decrease of power factor in IPMSM motor is related to the fact that for this motor operating at speeds exceeding the base speed it is necessary to increase the reactive component of the current in order to generate the armature mmf component oriented in the opposite direction to the PM excitation mmf, which in turn leads to weakening of the main magnetic flux in PMSM motor [3]. When main flux is weakened, then it is possible for the motor to operate at higher rotational speeds even though voltage at the output of power electronics converter (inverter) supplying the IPMSM motor is limited. Increase of rotor speed in IPMSM motor high above the base speed is therefore accompanied by significant deterioration of the power factor. In case of induction motor, where magnetizing of the magnetic circuit is provided by reactive power supplied from the network (and not by permanent magnets as in IPMSM motors), the weakening of the magnetic flux aimed at increasing rotational speed is accompanied by the decrease in the reactive component of the supply current, hence the improved power factor.

3. Economic analysis of the longwall shearer motors' drive operation.

In order to conduct economic analysis of applying different proposed variants of PMSM motors in the haulage drive of the shearer in place of currently used cage induction motors, we have run computer simulations aimed at calculating several parameters influencing economic effectiveness of the haulage drive of KSW-460NE longwall shearer. These parameters are shown in Table 3. The haulage drive of the shearer consists of two tractors. The assumed efficiency of the frequency converters supplying electric drive motors is 95 %.

Table 3. Selected parameters influencing economy of the haulage drive in KSW-460NE longwall shearer; wall worked is horizontal

Type of drive motor	Induction cage motors, 2 x dSKK(s) 180L4z			PM synchronous motors, 2 x PMSM 54 kW			PM synchronous motors, 2 x PMSM 70 kW		
Longwall shearer operational parameters	Working the 250m longwall at speed			Working the 250m longwall at speed			Working the 250m longwall at speed		
Parameters	5 m/min.	10 m/min.	20 m/min.	5 m/min.	10 m/min.	20 m/min.	5 m/min.	10 m/min.	20 m/min.
Electric power drawn from the network	23.9 kW	47.9 kW	92.8 kW	22.1 kW	44.7 kW	93 kW	21.9 kW	44.3 kW	91.1 kW
Efficiency of the drive system motor-converter	83.2%	82.6%	85.5%	89.8%	88.7%	85.3%	90.3%	89.5%	87%
Network load current (RMS)	49.3 A	85.2 A	134.7 A	27.7 A	56.1 A	116.7 A	27.5 A	55.6 A	114.4 A
Total energy consumption per whole wall	19.92 kWh	19.96 kWh	19.33 kWh	18.42 kWh	18.62 kWh	19.38 kWh	18.25 kWh	18.46 kWh	18.98 kWh
Thermal power released in drive motor	1.41 kW	2.97 kW	4.43 kW	0.58 kW	1.39 kW	4.51 kW	0.51 kW	1.22 kW	3.64 kW

On the basis of the conducted computer simulations of the haulage drive of KSW-460NE shearer with the following types of motors used:

- cage induction motors supplied from converters with scalar-control voltage inverters ;
- PMSM motors supplied from frequency converters with vector-control voltage inverters ad active rectifiers,

it must be stated that use of modern PMSM motors brings about positive economic effects at all real working speeds, i.e. up to 10 m/min. If we theoretically assume that the shearer might cut the wall at the highest possible catalog haulage speed (20 m/min), the haulage drive with PMSM motor rated at 54 kW (variant 1) would draw slightly higher active power from the network than currently used cage induction motor. However, application of the PMSM motor rated at 70 kW (variant 2) would lead to decrease in this input power.

The factors influencing improvement of economic effectiveness of the haulage drive in KSW-460NE longwall shearer, resulting from application of PMSM motors in the drive are shown in Table 4. These quantities are given as percentage values related to currently used drive with induction motors and with the assumption that the longwall worked is horizontal. The values of any parameters marked by "-" sign denote negative change in the economy of the drive, when PMSM motor is applied in place of currently used cage induction motor; the positive values denote improvement in a given parameter by appropriate percentage.

By comparing parameters given in Tables 3 and 4 we may infer that working a horizontal longwall at haulage speeds 5 and 10 m/min is much more effective economically when PMSM motors are used. The simulation results show significant and positive change in all parameters. In case of theoretcal working speed of 20 m/min the simulation results are not unequivocal. When PMSM motor rated at 54 kW is used, the power factor deteriorates and amount of electrical energy drawn from the network increases. In case of PMSM motor rated at 70 kW and for haulage speed equal to 20 m/min, the power factor decreases in relation to induction motor drive. However, as we mentioned earlier, the haulage speed equal to 20 m/min is used only during manoeuvring. Therefore if we evaluate shearer's economical attributes from the viewpoint of motor type used (three different motors are compared) we must take into account the fact that economic analysis for haulage speed 5 and 10m/min is much more significant.

Table 4. Factors improving economic effectiveness of the haulage drive of KSW-460NE lonwall shearer due to use of PMSM motors, in relation to induction motor drive; longwall worked is horizontal and 250 m long

Type of drive motor	PMSM motor rated at 54 kW. Working the 250m longwall at speed			PMSM motor rated at 70 kW. Working the 250m longwall at speed		
Parameters	5 m/min.	10 m/min.	20 m/min.	5 m/min.	10 m/min.	20 m/min.
Decrease in network power consumption	7.5 %	6.7 %	-0.2 %	8.4 %	7.5 %	1.8 %
Decrease in network load current (RMS)	43.8 %	34.2 %	13.4 %	44.2 %	34.7 %	15.1 %
Decrease of thermal power dissipated in the drive motor	58.9 %	53.2 %	-1.8 %	63.8 %	58.9 %	17.8 %
Increase of efficiency coefficient for drive system converter-motor	6.6 %	6.1 %	-0.2 %	7.1 %	6.9 %	1.5 %
Increase of power factor $\cos\varphi$	55.4 %	33.7 %	-26 %	55.1 %	33.4 %	-22 %

One parameter by which haullage drive of the shearer is characterized and which improves greatly when high-efficiency PMSM motors are used in this drive, is thermal power dissipated in the motors under given shearer's operating conditions. This power must be removed with the help of cooling system. Taking simulation data into account (horizontal longwall, haulage speeds 5 and 10m/min, Table 3), we may note that at these working speeds, the average value of thermal power dissipated in the haulage drive using PMSM motors is by either 56% (variant KOMEL1, 54 kW) or by *c.* 61.3 % lower (variant KOMEL2, 70 kW) in relation to drive using induction motors dSKK(s) 180L4z. If we assume that currently used cooling system will still be used in the shearer equipped with high-efficiency PMSM motors (where thermal losses will be much lower), it will be possible to increase operating time of the haulage drive during torque overloads. In case of KOMEL2 PMSM motor, this torque overload capacity will last longer and over a wider range of rotational speeds, since the torque-speed curve is more advantageous.

On the basis of the data set out in Table 2 we may conclude that working a horizontal longwall does not fully load the haulage drive motors of KSW-460NE shearer. Higher load is present when longitudinally inclined walls are worked. The maximum allowable longutudinal inclination of the wall (with the proviso that KSW-460NE shearer maintains its stability) is equal to 35°. Subsequent computer simulations of the haulage drive operation have been conducted for this inclination angle, both for working the wall and manoeuvring.

The electrical and mechanical parameters of a single tractor used in KSW-460NE longwall shearer are shown in Table 5. These parameters have been obtained by simulation for three different speeds of working the wall and manoeuvring for longitudinally inclined wall (inclination angle 35°).The speeds equalled 5 and 10 m/min; calculations have also been conducted for the maximum speed, when the shearer may continously operate at this inclination and resulting from the rated power of the haulage drive motors. Simulations have not been run for higher speeds since under such conditions the motors would have been overloaded and shearer's continuous operation would not have been possible.

Table 5. Selected parameters of the haulage drive in KSW-460NE longwall shearer; manoeuvring or working the wall with longitudinal inclination equal to 35°; different types of drive motors are compared

Type of drive motor	Asynchronous cage motor, rated at 45 kW, type dSKK(s)180L4z		PMSM - KOMEL1, rated at 54 kW		PMSM – KOMEL2, rated at 70 kW	
Mode of operation during measurements / Parameters	Manoeuvring at 5m/min.	Working the longwall at 5 m/min.	Manoeuvring at 5m/min.	Working the longwall at 5 m/min.	Manoeuvring at 5m/min.	Working the longwall at 5 m/min.
Motor's output power (mechanical)	14.4 kW	19.6 kW	14.48 kW	19.82 kW	14.48 kW	19.82 kW
Motor's input power (electrical)	16.13 kW	21.87 kW	15.25 kW	20.88 kW	15.14 kW	20.71 kW
Motor's power factor	0.751	0.826	0.992	0.982	0.995	0.987
Motor's efficiency	89.3%	89.6%	94.9%	94.9%	95.6%	95.7%
Motor's current (RMS)	47.85 A	58.96 A	41.74 A	55.49 A	53.51 A	71.25 A
Network current (RMS)	28.33 A	34.91 A	20.15 A	27.59 A	20 A	27.36 A
Mode of operation during measurements / Parameters	Manoeuvring at 10m/min.	Working the longwall at 10 m/min.	Manoeuvring at 10 m/min.	Working the longwall at 10 m/min.	Manoeuvring at 10 m/min.	Working the longwall at 10 m/min.
Motor's output power (mechanical)	28.71 kW	39.29 kW	28.84 kW	39.65 kW	28.84 kW	39.65 kW
Motor's input power (electrical)	32.1 kW	43.41 kW	30.43 kW	41.55 kW	30.21 kW	41.26 kW
Motor's power factor	0.824	0.872	0.992	0.982	0.995	0.987
Motor's efficiency	89.4%	90.5%	94.8%	95.4%	95.5%	96.1%
Motor's current (RMS)	51.08 A	65.24 A	42.21 A	56.18 A	53.96 A	71.96 A
Network current (RMS)	51.42 A	65.69 A	40.21 A	54.9 A	39.91 A	54.51 A
Mode of operation during measurements / Parameters	Manoeuvring at 11.5 m/min.	Working the longwall at 11.5 m/min.	Manoeuvring at 13.5 m/min.	Working the longwall at 13.5 m/min.	Manoeuvring at 17.5 m/min.	Working the longwall at 17.5 m/min.
Motor's output power (mechanical)	32.81 kW	45.07 kW	38.82 kW	53.52 kW	50.34 kW	69.39 kW
Motor's input power (electrical)	36.46 kW	49.74 kW	41.31 kW	56.51 kW	53.43 kW	72.87 kW
Motor's power factor	0.867	0.896	0.899	0.958	0.89	0.952
Motor's efficiency	90%	90.6%	94%	94.7%	94.2%	95.2%
Motor's current (RMS)	55.07 A	72.72 A	60.32 A	77.33 A	78.88 A	100.5 A
Network current (RMS)	55.46 A	73.25 A	54.58 A	74.66 A	70.59 A	96.28 A

Table 5 shows that (among others) independently of the shearer's mode of operation, when the wall is inclined at maximum possible angle, the efficiency of induction motors dSKK(s) 180L4z currently used in the haulage drive is on the average by several per cent lower than efficiency of proposed permanent magnet synchronous motors PMSM. Hence, for the same enforced operating conditions of the shearer (idential power at shaft of drive motors), the haulage drive using PMSM motors is characterized by smaller power input from the supply network. What is more, in relation to drive with induction motors, modernized haulage drives with PMSM motors will operate under identical conditions at much higher power factor cosφ; since active power demand will be less, significant decrease of current drawn from the network will be achieved. The increased rated power of PMSM motors will make it possible to attain higher haulage speeds when shearer works a longitudinally inclined wall, provided that currently used motor cooling system is retained.

In order to conduct analysis of economic gain obtained by using shearers with modernized haulage drives (with PMSM motors in place of induction motors) working longitudinally inclined walls, selected parameters influencing economic effectivess of longwall shearer KSW-460NE haulage drive have been set out in Table 6. These parameters have been calculated by computer simulations. The parameter denoted "Electric power drawn from the network" takes into account application of two electric motors in the haulage drive and efficiency of frequency converters supplying these motors has been assumed to be equal to 95 %.

Table 6. Selected parameters influencing economy of the haulage drive in KSW-460NE longwall shearer; wall worked is inclined by 35°; different types of drive motors are compared

Type of drive motor	Induction cage motors 2 x dSKK(s) 180L4z			PM synchronous motors, 2 x PMSM 54 kW			PM synchronous motors, 2 x PMSM 70 kW		
Longwall shearer's operational parameters / Parameters	Working the 250m longwall at speed			Working the 250m longwall at speed			Working the 250m longwall at speed		
	5 m/min.	10 m/min.	11,5 m/min.	5 m/min.	10 m/min.	13,5 m/min.	5 m/min.	10 m/min.	17,5 m/min.
Electric power drawn from the network	46 kW	91.4 kW	104.7 kW	44 kW	87.5 kW	119 kW	43.6 kW	86.9 kW	153.4 kW
Efficiency of the drive system motor-converter	85.1%	86%	86.1%	90.2%	90.6%	90%	90.9%	91.3%	90.4%
Network load current (RMS)	69.8 A	131.4 A	146.5 A	55.2 A	109.8 A	149.3 A	54.7 A	109 A	192.6 A
Total energy consumption per whole wall	38.33 kWh	38.08 kWh	37.93 kWh	36.67 kWh	36.46 kWh	36.73 kWh	36.33 kWh	36.21 kWh	36.52 kWh
Thermal power released in drive motor	2.27 kW	4.12 kW	4.67 kW	1.06 kW	1.9 kW	2.99 kW	0.89 kW	1.61 kW	3.48 kW

Basing on data set out in Table 6 we may state that using high-efficiency PMSM motors in the haulage drive will bring about positive economic effects at all speeds of working (mining) inclined longwalls. The haulage drive with currently used induction motors rated at 45 kW each, allows (theoretically) to work (mine) the longwall inclined at 35° with maximum speed of 11.5 m/min. If we use proposed PMSM motors rated at 54 kW, maximum working speed will increase to 13.5 m/min, and when motors rated at 70 kW are used, this speed will reach 17.5 m/min. This is approximately equal to the haulage speed of the shearer declared by the manufacturer, for the shearer equipped with original drive system and at catalog haulage speed 20 m/min. For both variants of PMSM motors, the increase in maximum working speed for the inclined wall is accompanied by the improved efficiency and power factor of the drive and decreased thermal power dissipated in the electric motors.

The factors influencing improvement of economic effectiveness of the haulage drive in KSW-460NE longwall shearer, resulting from application of PMSM motors in the drive are shown in Table 7. These quantities are given as percentage values related to currently used drive with induction motors. It has been assumed that the wall worked is inclined at an angle 35º.

The results are shown in Table 7 vs. the haulage speed. Since for every motor attainable maximum working speed is different, we have compared operational parameters affecting the economy of the drive for the speeds of 5 and

10m/min. Basing on Table 7 comparison, we may draw the conclusion that application of any variant of PMSM motor (KOMEL1 and KOMEL2) is much more advantageous than use of the induction motor.

Table 7. Factors describing economic efficiency of the haulage drive in KSW-460NE longwall shearer, due to application of PMSM motors; induction motors are the reference basis; wall worked is 250 m long and inclined by 35 °

Type of drive motor / Parameters	PMSM motor rated at 54 kW. Working the 250m longwall at speed		PMSM motor rated at 70 kW. Working the 250m longwall at speed	
	5 m/min.	10 m/min.	5 m/min.	10 m/min.
Decrease in network power consumption	4.3%	4.3%	5.2%	4.9%
Decrease in network load current (RMS)	20.9%	16.4%	21.6%	17%
Decrease of thermal power dissipated in the drive motor	53.3%	53.9%	60.8%	60.9%
Increase of efficiency coefficient for drive system converter-motor	5.1%	4.6%	5.8%	5.3%
Increase of power factor $\cos\varphi$	18.9%	12.6%	19.5%	13.2%

The greatest improvement in the operational parameters of the longwall shearer haulage drive may be observed in the quantity of thermal power dissipated in the motor. When high-efficiency PMSM motors are used, this parameter improves when the wall is inclined at an angle 35° same as in case of horizontal wall, at given operating conditions of the longwall shearer. If we consider the simulation data for wall inclined at 35° and for haulage speeds equal to 5 and 10 m/min, it may be observed basing on data set out in Tables 6 and 7, that at those speeds and in relation to drive using induction motors dSKK(s) 180L4z, the average value of thermal power dissipated in the haulage drive is lower by 53.6 % in case of KOMEL1 PMSM motor (54 kW) and by 60.8 % in case of KOMEL2 PMSM motor (70 kW).

Conclusions

On the basis of conducted computer simulations and analyses of haulage drive of the KSW-460NE longwall shearer we may state that each PMSM motor proposed for drive modernization (variant KOMEL1 54 kW, variant KOMEL2 70 kW) is characterized by better operational parameters than induction motor, both for the horizontal and inclined seams. Such parameters of electric drives as efficiency and power factor $\cos\varphi$ are significantly improved. This in turn leads to lessening of current drawn from the network supplying haulage drive. What is more, both PMSM motor variants make it possible to attain greater maximum haulage speeds when inclined walls are worked than in case of haulage drive using induction motors. The conducted simulations show that only if the haulage speed is equal to 20 m/min, the PMSM motor (variant KOMEL1, 54 kW) exhibits worse operational parameters than those of induction motor. However, this speed is used by the longwall shearer during manoeuvring only.

The improvement of the drive efficiency and power factor, which is accomplished by replacing the induction motors with PMSM motors in the haulage drive of the longwall shearer, will also lead to positive economic effects. In accordance with data set out in Tables 3, 4, 6 and 7, a significant decrease in the energy consumed by the haulage drive will be attained; decrease in current drawn from the network should allow a decrease in cross-sections of the supply cables; decrease of thermal losses in the motors should result in use (in modernized drives) of smaller, lighter and cheaper cooling systems.

For two proposed PMSM motor variants (KOMEL1 and KOMEL2), the greatest economic advantage is obtained by using the second variant in the haulage drive. This motor corresponds to the induction motor dSKK(s) 180L4z as far as dimensions are concerned. On account of much higher efficiency of KOMEL2 motor variant, this motor attains much higher rated power with unchanged overall dimensions (70 kW instead of 45 kW). The higher rated power will theoretically make it possible to increase haulage speeds when walls are inclined. However, the full power of this PMSM motor would probably not be used by KSW-460NE shearer, therefore this motor should rather be applied in bigger shearers.

PMSM motor, variant 1, rated at 54 kW, is characterized by efficiency and power factor similar to motor variant 2, and the improvement in operational parameters and resultant economic gain are similar as in case of variant 2. PMSM motor, variant 1, is smaller in relation to induction motor dSKK(s) 180L4z (one level down in shaft size of the series of types), and hence it is cheaper to make. That is why in the authors' opinion, this motor (variant1) is a better choice for modenization of haulage drive of the KSW-460NE longwall shearer.

In case of analyzed haulage drive of longwall shearer two drive systems are in existence (combine tractors), composed of two induction cage motors, supplied in parallel by one frequency converter with scalar control with superior speed controller. In this circuit torques generated by the motors are balanced, if we assume that slips of the motors loaded via mechanical gear with rigid toothed bar of the haulage drive are equal. However, when driving wheels (with involute profiles) of several tractors rotate, cyclic change in the rotational speed of the motors takes place, causing dynamic changes in the motors' slips. This in turn leads to modulation of the supply currents (RMS values) of the motors. When PMSM motors are applied in the modernized haulage drive, it will be necessary to supply each motor individually from a separate frequency converter with vector control and torque regulation.

On the basis of the conducted simulations [7,8,9] we may state that application of permanent magnet synchronous motors (PMSM) in haulage drives of longwall shearers in place of currently used cage induction motors, will bring about both economic and practical advantages, on account of better static and dynamic properties of PMSM drives.

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