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General purpose IE4 class synchronous motor with an integrated frequency converter

Streszczenie. *W artykule został opisany silnik synchroniczny z magnesami trwałymi ze zintegrowanym falownikiem. Pierwsza część opisuje wymagania stawiane napędom przemysłowym zmiennej prędkości o zakresie mocy w przedziale 1 – 3kW. Druga część artykułu opisuje budowę silnika oraz falownika. W ostatniej części przytoczone są wyniki badań sprawności, badań cieplnych oraz hałasu.* ***Uniwersalny silnik synchorniczny o klasie sprawnosci IE4 ze zintegrowanym falownikiem****.*

Abstract*. This article takes into consideration permanent magnets synchronous motor integrated with a frequency converter. First part describes briefly requirements for general, variable speed, industrial motor with power of around 1-3kW. Next part takes closer into consideration the motor used as well as an integrated frequency converter. Last, third part shows the test results (efficiencies, thermal and noise characteristics).*

Słowa kluczowe: PMSM, silnik zintegrowany, silnik synchroniczny.
Keywords: PMSM, integrated drive, synchronous motor.

Introduction

Due to new efficiency requirements IE3 and IE4 motors are already designed and enter the service. Up to now, industrial drives were powered almost only by asynchronous motors. In case of IE3 motors, there are no problems. Mostly these are improved and optimized IE2 motors. Many parts like lamination shapes, housings and shafts stayed the same like in IE2. The IE4 asynchronous motors must be designed from the beginning. They are low exploited, heavily over-dimensioned machines with very high material usage [1]. Due to low losses requirements, geometrical ratios are also different. To diminish influence of end-winding losses in stator and rotor and to keep motor's size according to the standards, outer diameter stays like in IE3 but the length is fairly extended. This phenomenon implies few problems: mechanical strength of A-bearing cover when motor is mounted directly to a gearbox (high weight of motor on long ram), machining of long housing (problem of mechanical stresses after molding process) and insertion of slot-closing insulation [2]. Some of these issues can be of course solved by new manufacturing processes. In the other hand, nowadays, due to optimization and automatization, more and more industrial applications required a variable speed drives. Market for high-end servo drives groves up. But there is a gap on the market between easy, constant speed drives and sophisticated, expensive servo drives. In this area low end, variable speed drives could be used. High efficiency is a demand but not as high dynamic and precision is required (like in servo drives). This gap could be perfectly filled by permanent magnets synchronous motors. Unlike servo motors, industrial PMSM are optimized in a different direction. Material usage and price are the most important factors. They can share some components with IE2/IE3 asynchronous motors. In most cases, housing and stator's laminations stay the same. Unfortunately downsizing is not possible because of standardization. Quite often, a short package is placed in the standard-length housing. Motor could be shorter but design and production of new parts (housing, bearing covers) are simply too expensive – see picture 1. Such IE4 synchronous motors are offered on market as easy and efficient solution for variable speed drives. To design and offer better product, parallel investigations in two directions were done. Firstly it was checked, how the free volume in the housing could be utilized in general and secondly – PMSM motor with concentrated winding was investigated [3]. After combining results and experiences of these two researches, an idea of a PMSM with concentrated winding and integrated with a frequency converter was created. It is obvious that this construction has several advantages over system where motor is separated from converter. In case of small industrial drives (power range from 1 to 3kW) not only gearbox and motor are important. The price of shielded cable between motor and converter is critical as well as position sensor with high IP factor. Also an issue with EMC compatibility could be critical sometimes. A motor with an integrated converter will solve all these problems.

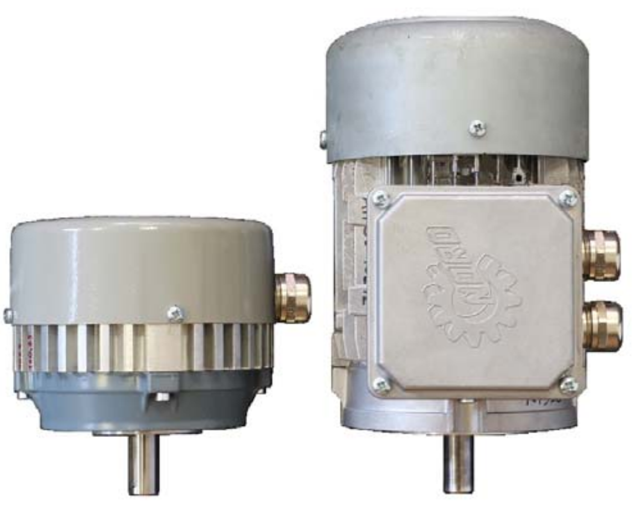

Fig. 1. 10 poles IE4 PMSM with package of 40mm in special, short housing (left) and IE3 asynchronous motor (right); both size 80 motors with 5Nm of nominal torque

Motor design

Concentrated winding in PMSM has fairly shorter end-windings in comparison to classic, 4 or 6 poles distributed winding. Therefore the copper losses are decreased. It allows increasing efficiency keeping constant package length or decrease package length keeping constant efficiency. Of course this is a general statement but the profit coming from lower winding resistance is higher than increased losses in iron (due to higher number of poles and higher operating frequency). Geometrical dimensions of 3 motors with similar output parameters are shown in table 1. First two motors are already in series production; 10 poles construction is in a prototyping phase. PM technology gives significant advantages over asynchronous.

Table 1. Three examples of general purpose, industrial motors – parameters and materials usage.

Parameter	Induction IE3	Synchronous IE4 (1)	Synchronous IE4 (2)
Power	0,75 kW	0,75 kW	0,75 kW
Speed	1500 RPM	1500 RPM	1500 RPM
Efficiency	82,5 %	90 %	90,5 %
No. of poles	4	4	10
No. of slots	24	24	12
LFe	105 mm	60 mm	30 mm
Stell thickenss	0,5 mm	0,5 mm	0,35 mm
End-winding height	29 mm	29 mm	10 mm
Weight of steel	6,5 kg	3,7 kg	1,65 kg
Weight of copper	1,9 kg	1,4 kg	0,55 kg
Weight of magnets	-	0,19 kg	0,12 kg

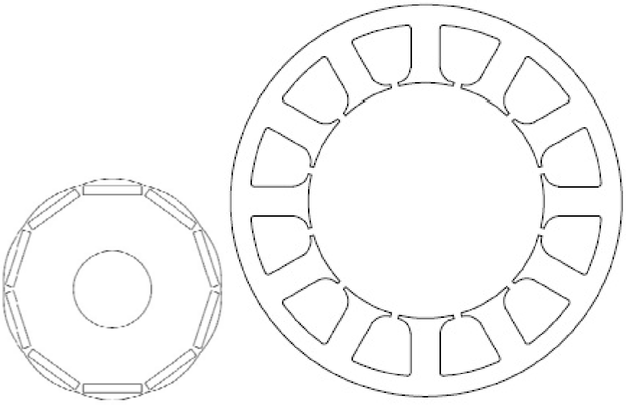

Fig. 2. Rotor and stator shape of the investigated motor

A concentrated winding technology creates next step to reduce the length of the active part of the motor.

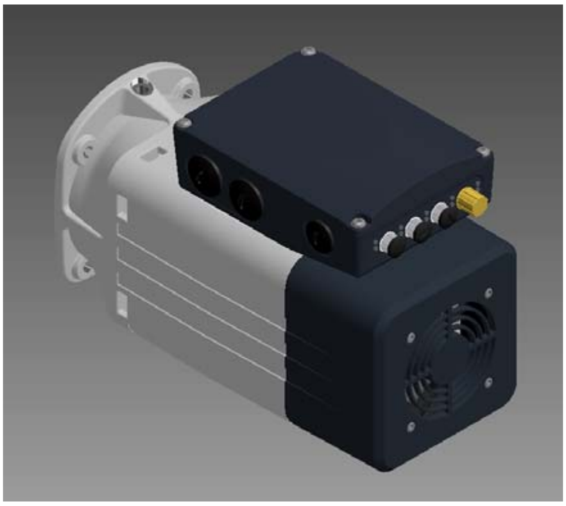

Fig. 3. General view of the first prototype of the integrated motor.

In picture 2 final shapes of rotor and stator are presented. This is the motor marked in table 1 as Synchronous IE4 (2). To optimize assembly process and material usage it was decided to support the motor's shaft only on one side (see picture 5). Two bearings are placed with certain distance one from each other. This distance is calculated so the radial stress in bearing is controlled and mechanical life-time is fulfilled as required. Thanks to this – inside the motor's housing the space is free of B-side bearing cover. General view of the prototype is show in picture 3.

Converter topology

Topology of the frequency converter is the same like in all general purpose industrial frequency converters. The power electronic circuit is shown in picture 4 (one phase version).

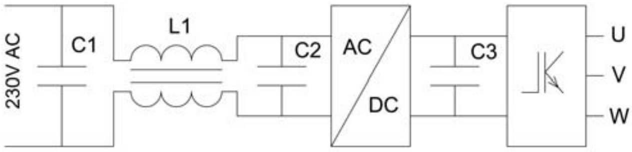

Fig. 4. Topology of frequency converter integrated with the motor.

The special feature in this unit is a reduced DC link capacitor. In the construction, capacitance is around 20μF. The reason of this is to save the space and improve the reliability [4]. Electrolytic capacitors with capacity of 470 – 1000uF would be suitable (for the power range around 0.75kW) and better for filtering but they require fairly more space. Of course this strategy implies reconsidering the winding of the motor and the control algorithm. First issue is a maximum, available permanently, DC link voltage. With infinitely high capacitance, theoretically 565VDC is possible when operating at 400VAC, three phases network. With a DC link capacitor of 20 – 30uF filtering process is poor and it could be said that motor is directly connected to DC voltage from 6-pulses rectifier. So the minimum DC link voltage can be as low as 490VDC. Now, the maximum possible output RMS value is 346V. Winding is designed to be able to operate at this voltage even at nominal speed and with 2,5 times overload. Second issue is DC link voltage swinging. 6 pulses rectifier gives voltage ripples of around 13%. The algorithm in frequency converter is able to deal in real time with a swinging DC link voltage. Without this control function, output torque can also contain harmonic ripples what can affect gearbox, load or just create an excessive noise. What also must be said – converter is split into two sections. Power module with gate drivers, DC link capacitor and current transducers are placed next to the heatsink, inside the main aluminum frame. The control unit with digital and analog inputs and outputs are placed over the motor, in the separated housing just little bit bigger than standard terminal box known from asynchronous motors. Even though this converter is a built-in converter has still many analog and digital inputs and outputs, PLC functions as well as control interfaces like CANopen, Profibus, AS interface, EtherCAT, Profinet, Device NET.

Thermal considerations and test results

Due to increased power of losses – two sources of heat in one housing as well as flat surface without extra cooling fins and temperature limit of electronic components (85°C) – forced cooling was chosen (picture 5). The motor is equipped with a 24V industrial fan. Construction is so designed that cold air goes first through the frequency converter's heatsink and then through the canals along the motor. This easy solution keeps power electronic elements cold. The warmer air is still able to cool down the motor – the part of construction which is not as critical as the electronic part. In comparison to standard housing of asynchronous motors where fins are around whole motor – here they are non-symmetric to decrease virtually size of the motor (picture 6). Due to high efficiency of the motor -

even reduced cooling surface is able to cool down the machine.

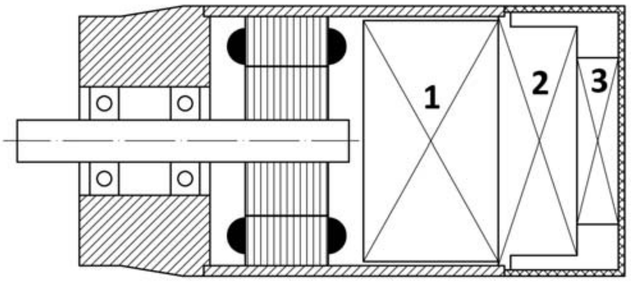

Fig. 5. Overview of the motor: 1 – power electronic, 2 – heatsink, 3 – fan

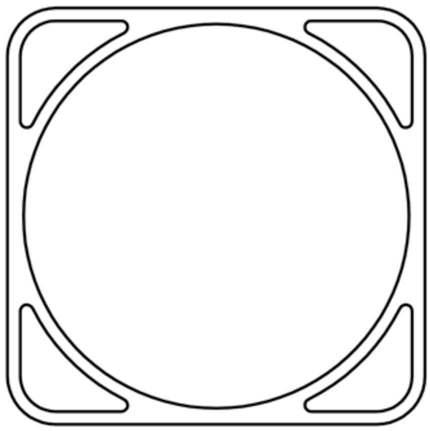

Fig. 6. Cross-section of the motor's housing

As it was tested – to keep temperature of the converter below 85°C – intermittent duty of the fan was sufficient. In the table 2 results of three different measurements are shown. Firstly motor was supplied by an external converter; the fan was permanently turned on. Then in the second test, motor was supplied by the embedded converter; the fan had turn-on threshold of 61°C and turn-off threshold of 42°C (processor temperature).

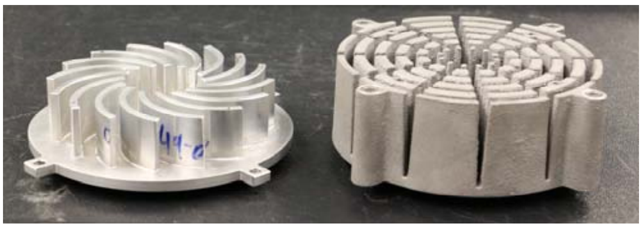

Fig. 7. New (left) and old (right) power module heatsink.

Table 2. Results of the thermal tests at 20°C, 5Nm, 3000rpm. Case 1 – external converter; Case 2 – embedded converter; Case 3 – embedded converter, 50% overload, fan duty 100%.

	Case 1	Case 2	Case 3
Fan usage [% of time]	100	~75	100
Housing [°C]	39	fan on:56, fan off:50	64
Winding [°C]	55	fan on:75, fan off:70	82
Heatsink [°C]	-	fan on:52, fan off:36	34
Motor losses [W]	115	115	181
Converter losses [W]	-	40	58

Last test is a 50% overload test. Due to low temperature rise at power module heatsink a new version was designed. It is shown in picture 7. New, improved shape of cooling fins together with reduced height gave a reduction of the total length of the motor by 15mm keeping similar temperature rises (temperature of the cooling fins was around 2 degrees Celsius higher than before and due to lower heat capacitance – the duty period of the fan was shorter).

Noise test results

A synchronous motor with fractional slot, concentrated winding can be in some cases a source of an excessive noise [5]. In the investigated motor, 10 poles and 12 teeth is a combination good from the point of view of high average torque (high winding factor), relatively low supply frequency (250Hz at 3000rpm) what keeps iron losses on low level even with 0,35mm steel. A disadvantage of this construction is a magnetic pull with two periods around the stator. Such magnetic pull is symmetrical and doesn't affect bearings but divides the stator's package and housing into two 180° spans [6,7]. This situation is the worst case. Due to lack of the silent enough load machine it was decided to test the motor via worm gearbox (ratio 1:10). The worm gearboxes are known for smooth and silent run so a gearbox will not give an extra, high level noise. The noise coming from the load machine (magnetic powder brake) running at speed 10 times lower than a motor can be also neglected. In addition – test results were compared with three other motors (three PMSM – one with 4 poles and second 10 poles – both with standard housing with length of 130mm, third – also 10 poles, same electromagnetic construction but short housing – only 40mm). Results are shown in the table 3. What also was found during tests and mechanical measurements – the idea with two bearings on the same side is not good. The small distance between bearings together with mechanic manufacturing tolerances of bearings and housing (radial clearance) causes sometimes excessive rotor vibrations. Also air gap around the rotor is not equal what can cause also electric problems with unsymmetrical currents.

Conclusion

Both – thermal and noise tests have proven that construction of the motor is not optimal. From the thermal point of view the main part of the housing of the motor is correct and shows good thermal properties. 4 cooling canals along the motor have big enough surface to cool down the winding and magnetic core. Heatsink of the power electronic seems to be still oversized.

Table 3. Results of noise tests. All motors size 80, torque 5Nm, 8kHz converter switching frequency. A – 10 poles PMSM, converter inside; B – the same magnetic circuit like A but short housing and no converter inside; C – 4 poles PMSM, D – 4 poles asynchronous motor.

	A	B	C	D
Load 1500 rpm	64 dB	53 dB	55 dB	56 dB
No load 1500 rpm	61 dB	51 dB	54 dB	51 dB
Load 3000 rpm	70 dB	66 dB	63 dB	68 dB
No load 3000 rpm	65 dB	62 dB	63 dB	63 dB

Its temperature is lower than motor's housing temperature by 14°C to 30°C. It must be found whether heatsink should have just higher thermal factor ([W/°C]) and be shorter or it should be tried to improve thermal connection between heatsink and housing to use also the heatsink to cool down the active part of the motor. In the second variant probably improved shape of the housing (especially thickness of the walls) must be considered to improve thermal connection.

Noise test has revealed that housing is probably not optimal. The same magnetic circuit but placed in a different housing (as long as magnetic core) gave fairly lower noise both at no-load and load condition. It must be mentioned that the housing of the integrated motor has the largest area of all motors, so the source of noise is also significantly greater than in other motors. What also must be said is that a cover of the heatsink had some resonances so the average noise contains also this mechanical resonance. The fan cover must be reconsidered too. As it was mentioned – in the improved motor the rotor must be supported on two sides. It implies of course more complicated assembly procedure but will reduce the vibrations and noise.

Generally the idea of an integrated drive with the synchronous motor is able to be realized. First prototype has proven that the geometrical dimensions and material usage are similar or lower than in cases where the frequency converter is not directly placed in the same housing. Costs of assembly are fairly decreased because of reduced number of elements in comparison to other solutions.

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