Krzysztof KRYKOWSKI[2], **Zbigniew GAŁUSZKIEWICZ**[1], **Patryk GAŁUSZKIEWICZ**[1],
Janusz HETMAŃCZYK[2], **Dariusz CAŁUS**[1]

Czestochowa University of Technology, Faculty of Electrical Engineering, Institute of Electrical Power Engineering (1), Silesian University of Technology, Faculty of Electrical Engineering, Department of Power Electronics, Electrical Drives and Robotics (2)

doi:10.15199/48.2019.08.30

High-speed Permanent Magnet Brushless DC Motors, Properties and Prospective Applications

***Abstract**. The paper describes motors used in high-speed electrical drives. Additionally, basic facts describing the PM BLDC motor have been given, focusing in particular on its design and construction as well as on its performance assessment. The paper also presents a comparative analysis of induction motors and permanent magnet motors. Moreover, various possibilities of application and innovative uses of the PM BLDC motor have been explored, like the use of the motor in a reverse scenario as a kinetic energy storage bank.*

***Streszczenie**. W publikacji zaprezentowano silniki stosowane w wysokoobrotowym napędzie elektrycznym. Przedstawiono również podstawowe wiadomości o silniku PM BLDC skupiając się na budowie tego typu silnika oraz na jego ocenie. W artykule zawarto również zestawienie porównawcze silników indukcyjnych z silnikami wzbudzanymi magnesami trwałymi. Ponadto opisano możliwości oraz innowacyjne zastosowania wysokoobrotowego silnika PM BLDC, takie jak na przykład wykorzystanie go w wersji odwróconej jako magazynu energii kinetycznej. (**Właściwości i potencjalne zastosowania silnika wysokoobrotowego PM BLDC**)*

Keywords: High-speed PM BLDC Motors, high-speed electrical drives, kinetic energy, energy storage.
Słowa kluczowe: wysokoobrotowe silniki PM BLDC, wysokoobrotowe napędy elektryczne, energia kinetyczna, magazyn energii.

Introduction

Technological advancement contributes to the increase of applications of high-speed electrical drives.

Drives with high-speed motors are used in a wide range of manufacturing industries including machine industries, car manufacturing, model making, dentistry, military industry as well as in devices producing electrical energy from biogas or steam, to mention just a few. The ideal high – speed motor should be small in size, have high performance, be simple to operate and reliable. Currently mass produced high-speed motors have speeds of about 20 – 30 000 rpm.

Permanent Magnet Brushless Direct Current motors (PM BLDC), are particularly efficient where high-speed applications are involved. The PM BLDC motors are characterized by a relatively simple design, high specific power, relatively small dimensions, a low moment of inertia and good dynamic properties [18]. They are smaller and require simpler control circuits than induction motors. PM BLDC motors are also very reliable which makes them particularly suitable for high-speed applications [6].

Motors used in high-speed electrical drives

It is commonly assumed that high-speed motors are motors working at a speed exceeding 10 000rpm [1, 2]. The authors of the present paper, however, are of the opinion that a distinction should be made for motors of a lower, medium and higher speed ranges. It is therefore suggested that motors having power within the range of a few kilo watts should be distinguished as follows:

- Lower speed range, including motors with speeds ranging from 10 000 – 40 000 rpm;
- Medium speed range, including motors with speeds ranging from 40 000 – 70 000 rpm;
- Higher speed range, including motors with speeds ranging from 70 000 – 100 000 rpm.

Motors with speeds exceeding 100 000 rpm should be named ultra-high-speed motors.

Currently the most popular high-speed motors are:

- Electromagnetic synchronous motors;
- Induction motors;
- PM BLDC motors;
- Direct Current motors;
- Permanent Magnet Synchronous Motors (PMSM);
- Hysteresis motors.

The above mentioned motors are produced for lower high -speed motor speed ranges and most of them are not suitable for applications with speeds exceeding 20 000 rpm. The only motors which can achieve speeds in the medium and higher ranges are the PM BLDC and PMSM. The advantage of PM BLDC motors over the PMSM is simpler design and simpler control circuits. Due to the above the PM BLDC motors are the main focus of the present paper.

Basic information about the PM BLDC motor

Principles of operation of high-speed motors are the same as in the case of other types of PM BLDC motors [12, 13]. PM BLDC motors characterized by a low moment of inertia making them ideally suitable for high-speed applications [2, 5, 6]. In the case of a high-speed motor, one-pole pair constructions are recommended. The schematic diagram of a PM BLDC motor with one pole pair is presented in figure 1. The particular phase windings are switched on and off sequentially by bridge transistors and they generate magnetic field with six specific vector positions.

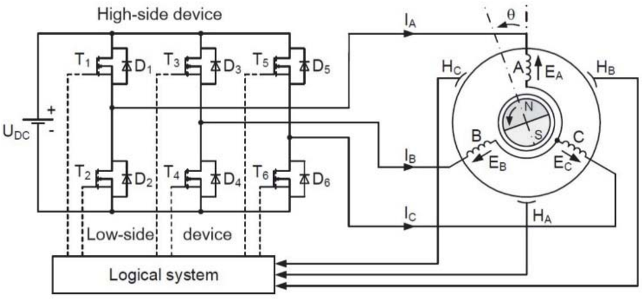

Fig.1. PMBLDC motor scheme with an electronic commutator

The flux linked to stator and generated originally by rotor magnet changes its position continuously. While it is different in the case of a stator flux, where the vector 'jumps' from one position to another and there are six possible positions in all. The flux linkages related to different phase windings, corresponding position sensor signals (usually Hall sensors are used), phase and line EMFs and phase current waveforms for a motor with one pole pair are shown in figure 2. The position sensors signals, after some processing conducted in logical circuit, determine switching ranges of electronic commutator [3].

The waveforms shown in figure 2 relate to a particular situation, where Hall sensors are placed at the axes of different phases. In practice, we often find a situation where Hall sensors are displaced in relation to these axes. We can also find cases where Hall sensor brings about some measurement error.

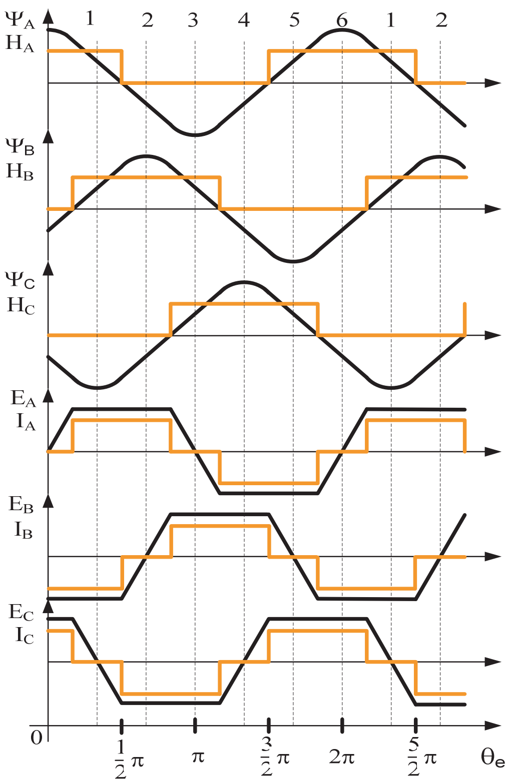

Fig.2. Voltage, current and flux linkages waveforms in ideal PM BLDC motor

Now, if we assume that for an analyzed time interval (instant) the motor current and phase electromagnetic force (EMF) are constant, the following expressions (1) and (2) are obtained, presenting electromagnetic torque (T_{ek}) for each phase.

$$T_{ek} = \frac{e_k i_k}{\omega} \tag{1}$$

and summary electromagnetic torque (T_e)

$$T_e = \sum_{k=1}^{3} T_{ek} \tag{2}$$

where: e_k – EMF of k-th phase; i_k – current k-th phase; ω – angular speed.

Equations (1) and (2) describe the component of electromagnetic torque due to k-phase winding operation and total magnetic torque generated by the motor. Now, we introduce excitation coefficient for k^{th} phase $K_{fk}(\theta_{ek})$ and relative excitation coefficient $k_{fk}(\theta_{ek})$ as a function of electrical degree of rotation which may be expressed as (3).

$$K_{fk}(\theta_{ek}) = \frac{E_k}{\omega} = p_b \frac{E_k}{\omega_e} = p_b k_{fk}(\theta_{ek})\Psi_m \tag{3}$$

where: E_k – EMF of k-th phase; p_b – number of pole pairs; ω_e – electrical angular velocity; Ψ_m – flux produced by magnet.

Due to the fact that within the valve operation range the excitation coefficient for an ideal motor is constant, the relationships between current and electromagnetic torque of k^{th} phase as well as speed and EMF may be expressed as (4) and (5).

$$T_{ek} = i_k K_{fk}(\theta_{ek}) = p_b k_{fk}(\theta_{ek})\Psi_m i_k \tag{4}$$

and:

$$e_k = \omega K_{fk}(\theta_{ek}) = p_b k_{fk}(\theta_{ek})\Psi_p \omega = k_{fk}(\theta_{ek})\Psi_m \omega_e \tag{5}$$

where: Ψ_p – summary magnetic flux

In a real PM BLDC motor there are inductances, phase currents and corresponding component torques which include exponential components [2]. As a result, real waveforms are different from ideal ones (Fig. 3).

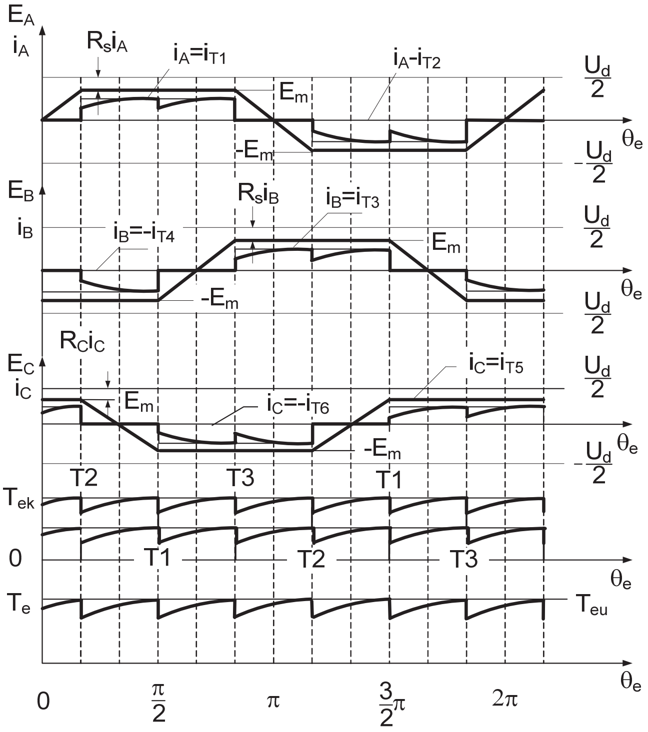

Fig.3. Electromagnetic torque waveform construction in a real motor

PM BLDC motor as energy storage [6, 14, 15, 16]

Energy stored in rotational mass is expressed by (6).

$$W_k = \frac{1}{2} J\omega^2 \tag{6}$$

where: J – momentum of inertia.

From dependency (6) it follows that energy stored changes together with the square of rotation speed, which means that it is best to apply maximum rotation speeds. The element used for storage of energy is the rotor with a high momentum of inertia. The momentum of inertia of the rotor may be increased by replacing the classical construction with a reversed construction having an external rotor. The external rotor then becomes a kind of thick-walled pipe with an inertia momentum expressed by dependency (7).

$$J = \frac{1}{2}\pi l \rho \left(R_e^{4} - R_i^{4}\right) \tag{7}$$

where: l – length or height of cylinder; ρ – density (e.g. for steel – $7.8 \cdot 10^3 \text{kg/m}^3$); R_e and R_i, – radius of pipe - external and internal.

That kind of construction requires the use of durable steel and special composite materials in order to enable the development of a hybrid construction.

PM BLDC motor design

The electromotive force induced in phase windings of a PM BLDC motor should be constant during active operation.

Due to the small size of the engine, it is not possible to develop adequate electromotive force by choosing the winding factor.

The simplest motor design that ensures constant electromotive force for the valve active operation range is a construction with full-pitch winding and a radially magnetized magnet where the arc is equal to or greater than 120°.

The design principles of such a motor and the expected phase EMF wave courses are shown in figure 4.

The design features associated with the minimization of power losses were also taken into account [17, 19].

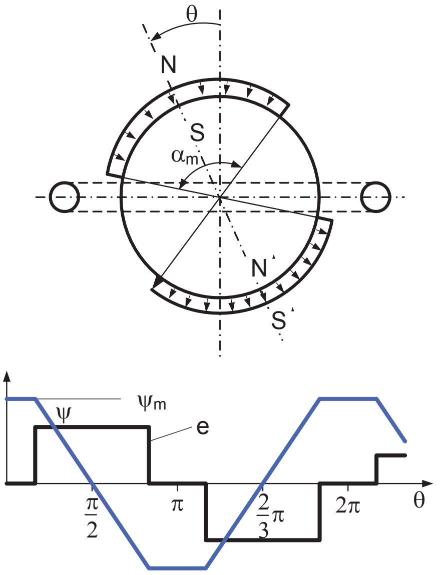

Fig.4. Inducing of EMF in a single stator turn for ideal winding and radial magnetization: system diagram and EMF waveform

a)

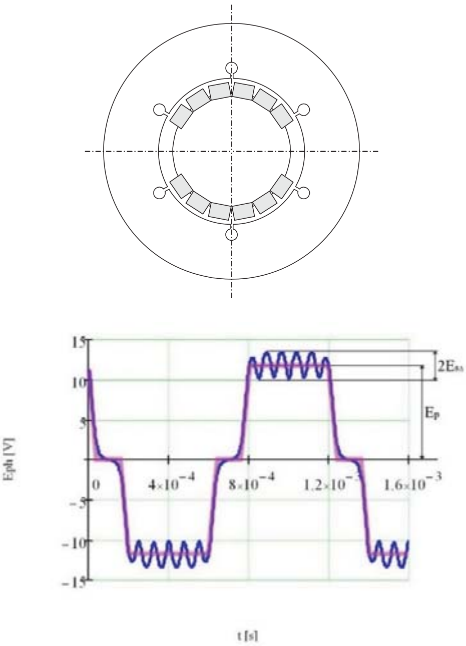

Fig.5. a) Layout of the proposed motor cross-section, b) Phase EMF waveforms for half-open slots.

Due to the low availability of magnets with appropriate sizes and type of magnetisation in series of experiments carried out at the Department of Power Electronics and Robotics of the Silesian Technical University [1, 2, 5] we have suggested replacing the arc shaped magnets magnetised radially by magnets with a rectangular cross-section.

The developed rotor construction and phase EMF waves for neodymium magnets and half-open slots are shown in figure 5

Figures 6, 7a and 7b show measured phase EMF waveforms and phase current waveforms in a motor with magnets and windings as in the layout in figure 5.

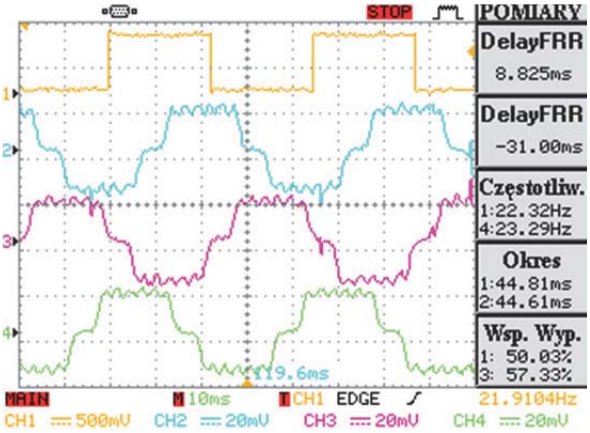

Fig.6. Phase EMF waveforms and signals from one of the Hall sensors, measured at reduced engine speed.

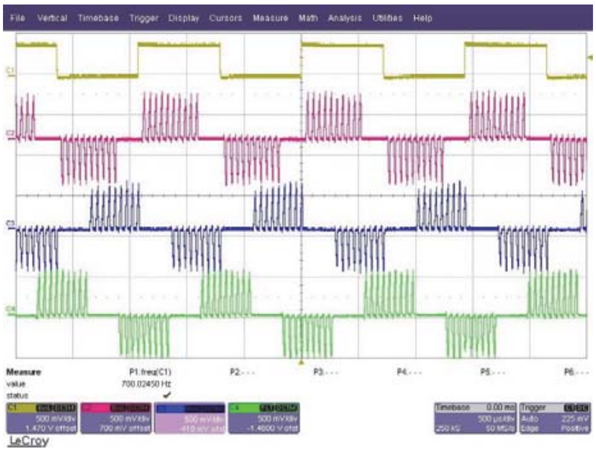

Fig.7a. Phase current waveforms of an engine rotating at a speed of 42 000 rpm with a small load taking into account PWM.

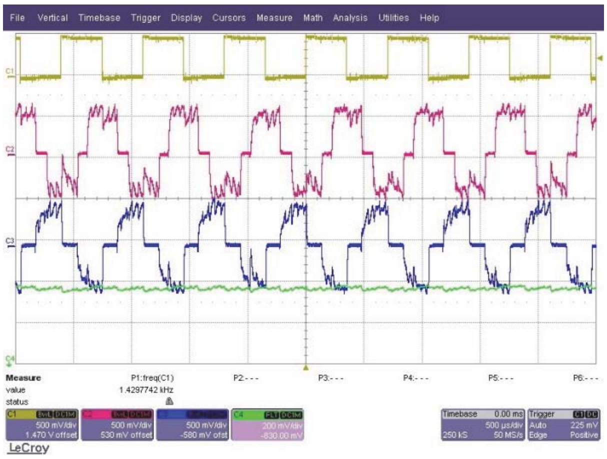

Fig.7b. Phase current waveforms of an engine rotating at a speed of 85 786 rpm with a small load.

Basing on research carried out at the Department of Power Electronics and Robotics of the Silesian Technological University a prototype of a high-speed PM BLDC was developed. The prototype has 800 W power and rotation speed of 60 000 rpm. The engine was made by Megatech-Kalety company.

A comparison of induction motors and PM (permanent magnet) motors.

In a number of papers, including [3] it is said that PM BLDC motors may replace any other electrical machine and therefore are the drive of the future. Some of the characteristic features are unique to this type of motor. The important and unique features of the PM BLDC motor include:

- torque overload to about 5-7 times depending on the nominal torque;
- smaller size and mass;
- simple control of rotation speed and speed stabilization;
- the ability to operate in groups with individual speed correction;
- brake torque for a stopped motor;
- linear speed independent of rotation speed;
- higher operation dynamics;
- less critical size of air gap;
- simpler braking systems with energy recovery;
- a better overall efficiency including the control system.

PM BLDC features similar to other types of motors:

- overload capacity up to short circuit;
- all motor types require energy electronic systems;
- Costs, bearing requirements are comparable to similar rotation speeds, PM BLDC motors performing slightly better as with the same bearing size a greater power may be achieved.

The only disadvantage of the PM BLDC motors is its slightly higher cost when compared to other types of motors. This is because permanent magnets are used. However, the PM BLDC motor operating in combination with an electronic commutator is cheaper than an induction motor with an inverter.

Comparison of the two discussed types of motors is presented in Table 1.

Table 1. A Comparison of Induction motors and PM BLDC motors

Characteristic feature	Induction motor	PM BLDC motor
Torque overload	2-3 (-)	Greater (+)
Current overload	Short-circuit current (=)	Short-circuit current (=)
Size and mass	Larger (-)	Smaller (+)
Torque - speed characteristics	Contains an unstable part (-)	Linear independent of velocity (+)
Operational dynamics	(-)	better (+)
Type of power supply	Inverter (=)	Electric commutator (=)
Speed drive systems	Complex	PM BLDC – simpler (+)
Group work possible	Yes – individual adjustment of speed impossible (-)	Yes – individual adjustment of speed possible (+)
Brake torque of stationary engine	No (-)	Yes (+)
Efffect of load on motor efficiency when braking	May be limited (-)	May be easily limited (+)
Air gap	Small (-)	May be expanded (+)
Braking with energy recovery	Complex (-)	Simpler (-)
Bearings selection	Similar but smaller power on same bearings (-)	Similar but greater power on same bearings (+)
Losses in rotor in stator	Greater (-) Greater (-)	Smaller (+) Smaller (+)
Overall efficiency	Smaller (-)	Greater (+)
Heating and cooling	Greater losses – more complex cooling systems (-)	Smaller losses – simpler cooling sysytems (+)
Cost of magnets	No magnets (+)	Expensive magnets (-)

(+) positive feature; (-) negative feature; (=) comparable feature

Upon comparison of the two types of motors, it may be concluded that the main advantage of induction motors with a squirrel cage rotor is their relatively simple yet reliable production technology. The main downside of induction motors is the requirement of electrical energy for the creation of a magnetic field as well as the fact that the current at idle speed in low power induction motors may reach up to 40% of rated value.

While PM BLDC motors do not need additional energy consumption for the process of magnetisation.

Therefore, when energy efficiency of induction and PM BLDC motors of similar basic parameters is compared, it is always to the advantage of the latter.

Hall sensors' application features

Average electromagnetic torque T_{eav} of the high-speed PM BLDC motor expressed by (8) is defined by integration of the dependence of the electromagnetic torque on the rotation angle Θ between two switching periods.

$$T_{eav} = \frac{2}{\pi} \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} T_{max} \; cos(\Theta) \; d\Theta \tag{8}$$

where: T_{max} – maximal torque of motor.

One of the problems pertaining to high-speed PM BLDC motors is fast responsiveness of every part of the system, which is due to the high value of angular velocity. Angular velocity at 85 786 rpm (see Fig.7) leads to phase switching period (π/3) of less than 120 μs, for the projected speed 100 000 rpm, while the switching period of bridge transistors decreases to 100 μs. Accordingly, slight delays of several microseconds can cause real changes in the electromagnetic torque. It should be noted that typical Hall sensors have rising time near 1-2 μs [7, 8] that can increase delay of phase switching period up to 7° for the speed 100 000 rpm.

An additional factor is the error from the moment of inaccurate operation of the Hall sensors, which were used to identify the position of the rotor of the PM DLDC motor. This error occurs due to a certain threshold of the sensor operation. Typical industrial Honeywell Hall sensors can sense varying magnetic flux from 4 to 25 mT (with the technological spread of parameters according to the datasheets [7] and [8]. In the worst case this range may be from 2 to 40 mT) (see Fig.8, that is based on method from [9] for maximum magnetic flux $B_{max} = 0.25$ T per unit scale).

In the case of the switching angular error δΘ, the mean value of the torque will change as expressed in (9).

$$T_{eav} = \frac{2}{\pi} \int_{-\frac{\pi}{6}+\delta\Theta}^{\frac{\pi}{6}+\delta\Theta} T_{max} \; cos(\Theta) \; d\Theta \tag{9}$$

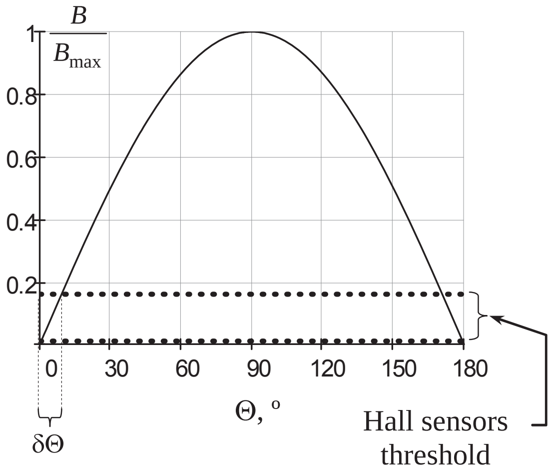

Fig.8. Illustration of the position sensor error [9].

At the same time, the torque pulsations between commutations increase, which is associated with a decrease in the value of the minimum motor torque as expressed in (10), (see table 2 that was calculated using the method described in [9]).

$$T_{min} = T_{max}\ cos\left(\frac{\pi}{6}+\delta\Theta\right) \tag{10}$$

Table 2. Effect of the switching angle error relative to the optimal value of the electromagnetic torque and the magnitude of the torque pulsations [9].

Error of the switching angle [degree]	Degrading the average moment [%]	Growth of the torque pulsations relative to the mean value [%]
5°	0.4	4.7
10°	1.5	10.0
15°	3.4	15.9
20°	6.0	22.3
25°	9.4	29.2

New applications and opportunities of high-speed PM BLDC

The present and prospective applications of high-speed PM BLDC motors include:

- Energy storage systems having a capacity of several dozen megawatt hours, which enable this kind of motor to be used as a machine for the storage and recovery of energy in kinetic form for as long as 60-70 hours. The potential use of these energy storage devices for the storage of wind and solar energy, as well as day/night operation makes it possible to significantly reduce costs of powering many devices or increase the number of smaller recipients. This also enhances energy production efficiency by professional energy users in night time and the full use of energy surplus produced by wind farms, photovoltaic and other sources having an energy surplus at certain times. Energy storage systems designed in this way allow for the overload in energy transfer to an energy receiver with power 5-7 times larger than nominal power. They may also be used as large UPS or, for instance as power systems for quick charging of electric cars [10].
- In the production of bearings for grinding bearing ring raceways – speed up to 100 000 rpm.
- High-speed milling plotters with a speed in excess of 40 000 rpm.
- Electro-spindles operating at a speed of 30 000 rpm.
- Machining centers – the application of high-speed PM BLDC motors makes it possible to reduce the time needed for the performance of many repetitive operations such as grinding, drilling and polishing; this leads to the enhancement of cost effectiveness in the production process.
- Tankless compressors operating with the air output switched off, the control system reduces rotation speed up to a value maintaining the set pressure. After the air inlet valve is opened the rotation speed increases up to a value which allows the maintenance of the assumed pressure.
- Military use applications suitable for devices which change location fast e.g. fast weapons, flying vehicles allowing a fast adjustment of the flight trajectory and many other similar applications.
- Cutting machines for extremely hard materials.
- Ultracentrifuges, centrifugal pumps and vacuum pumps.
- High-speed electric drills for printed circuits.
- Electric power generators suitable for industrial waste gases, biogas operating at a speed of 60-80 thousand rpm. The exhaust velocity of the gases makes it possible to achieve such rotation speed ranges of the power generator with a significant reduction of its size. Output voltage of such a power generator after rectification may be used for powering an inverter operating at a frequency of 50 Hz.
- High-speed balancing machines.
- In the automotive industry – turbocharging at a speed of 100-150 thousand rpm, ensuring the operation of the turbine after ignition during the entire time the engine is operating independently of the rotation speed.
- Household appliances operating at a speed of 30 -40 thousand rpm.
- Electric tools operating at a speed of 30 -60 thousand rpm.
- As substitute for asynchronous engines, making it possible to give a larger load to PM BLDC with a smaller power. Reaching overload capacity through torque by 5 - 7 times of the nominal depending on the engine make [11].

It should be emphasized that high-speed PM BLDC motors can also operate in conditions where it may be necessary to exceed the motor rated torque. This quality facilitates fast energy recovery from storage devices with currents five to seven times greater in relation to the rated current (during charging). They may also be used is special types of milling machines for the simultaneous milling of both ends of the welding machine, where the short operating time requires the torque to be exceed fivefold.

Summary / Conclusions

High-speed motors rotating at a speed of 60 000 rpm may be used in numerous ways. An example of a motor having a power of 800 W and a speed of 60 000 rpm is shown in figure 9. PM BLDC motors can be used in many more ways after modification. It should also be noted that there is ongoing research on how to increase its speed range to 100 000 rpm or even more. The expertise gained in course of the production process of these motors may be useful in the development of other types of motors. One of the most promising trends is using this kind of motor in cars for turbocharging after ignition.

Another good idea is constructing a reversed generator as a storage device for kinetic energy.

Figure 10 shows a system for the processing and recovery of energy to the power energy grid. The system is designed for the processing of surplus electrical energy into mechanical energy in a power energy grid, the energy is then stored in the rotor mass of a reversed PM BLDC electrical motor and an attached flywheel. The energy stored may then be processed again into electrical energy and transferred to the power energy grid when needed.

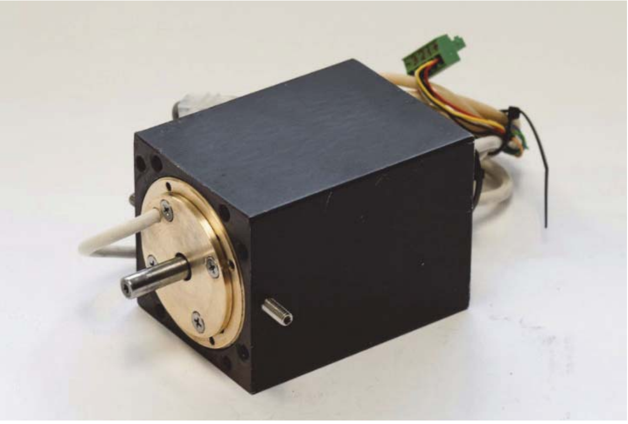

Fig.9. A motor with 800 W power and a speed of 60 000 rpm produced by Megatech-Kalety

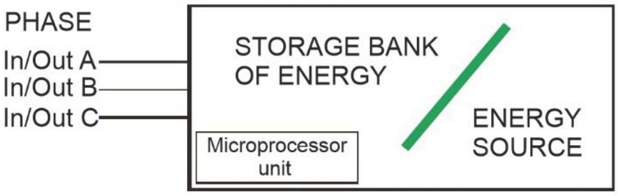

Fig.10. Energy storage bank [6]

Energy storage devices that transform electrical energy to kinetic energy and vice versa have been known for a long time. The presented solution, however differs from previous concepts because in this case the engine has three functions; that of the motor, power generator, and energy storage device. The device operates through the acceleration of a certain mass to an speed. Kinetic energy depends on the mass and speed. Therefore, not only the rounds need to be increased, but also the maximum mass has to be reached at the smallest possible size.

Such a device is unprofitable for an individual recipient assuming that, he uses 1 MWh, a month, and the energy storage device has 1 MWh, that is a thousand times more energy than the individual recipient’s monthly energy demand.

Energy storage devices are large and able to provide energy for an entire factory, they can be a UPS for a big company, dealing in, for example computers, where it can be used to maintain continuous energy supply for computers or other devices powered by electricity in cases of breaks in power supply. The device can also work as a backup for energy systems. Where the power line supplying electrical energy to a town is long, the power is only 100 kW.

Devices operating on this line require 150 kW at peak hours. That is why in normal conditions it is impossible to supply them with energy. If, however, at the end of the line there is a storage device, the energy stored at night at low demand may be used at day time, when the demand automatically rises once companies start operating. This can also be advantageous for companies operating in a shift system, then energy is stored and used precisely when it is needed.

At present the greatest challenge is finding a solution that would enable fast charging of electric cars. The development of the electric cars industry creates a growing demand for electrical energy. The research carried out shows that the consumption of energy and power required to supply a million electric cars increases the demand for power and energy by several percent.

Satisfying such a large demand for energy means that large power plants have to be built. However, the implementation of such a plan is extremely costly and time consuming, and all the network grids and transformers will not be able to transfer amounts of energy that large. It is however, possible when energy storage concepts are used. At night there is approximately 50 to sometimes even 70 percent of power reserve from the currently existing energy sources. The reserves are not consumed, as the energy demand at night is not that big. If that energy is stored at night, not only will the energy from existing power plants be consumed, but also energy from wind farms may be used, whereas now the wind farms are exploited at day time only, as there is no need for so much energy at night.

Electric car producers strive to create a system that would enable the fastest possible charging of the cars. The optimal time of charging for such a system would be approximately 10 minutes. The aim is to make charging time comparable to the time needed to fill up a car with conventional fuels. Everything depends on whether the car is able to take in such huge amounts of energy. Until there are devices constructed that are able to take in large amounts of energy, car producers will not be working on solutions that result in additional problems with the car construction.

Energy storage devices make it possible to charge an electric car in 5 minutes, and are enough to drive for a distance of 200 km. This is an equivalent of 40 kWh. In this case, taking into account the efficiency of the devices used for charging, the power need is approximately 0.5 MW. The solution of this problem would be the construction of an energy storage device with a power of 0.5 MW that could have the capacity to charge electric cars. The energy may come from wind power plants, photovoltaics and conventional power plants producing energy at night.

Authors
prof. dr hab. inż. Krzysztof Krykowski, Silesian University of Technology, Faculty of Electrical Engineering, Department of Power Electronics, Electrical Drives and Robotics, Bolesława Krzywoustego Street 2, p.o. box 44-100 Gliwice, Poland, e-mail: krzysztof.krykowski@polsl.pl,
mgr inż. Zbigniew Gałuszkiewicz, Czestochowa University of Technology, Faculty of Electrical Engineering, Institute of Electrical Power Engineering, Armii Krajowej Avenue 17, p.o. box 42-200 Częstochowa, Poland, e-mail: z.galuszkiewicz@el.pcz.czest.pl
mgr inż. Patryk Gałuszkiewicz, Czestochowa University of Technology, Faculty of Electrical Engineering, Institute of Electrical Power Engineering, Armii Krajowej Avenue 17, p.o. box 42-200 Częstochowa, Poland, e-mail: p.galuszkiewicz@el.pcz.czest.pl
dr inż. Janusz Hetmańczyk, Silesian University of Technology, Faculty of Electrical Engineering, Department of Power Electronics, Electrical Drives and Robotics, Bolesława Krzywoustego Street 2, p.o. box 44-100 Gliwice, Poland, e-mail: janusz.hetmanczyk@polsl.pl
dr inż. Dariusz Całus, Czestochowa University of Technology, Faculty of Electrical Engineering, Institute of Electrical Power Engineering, Armii Krajowej Avenue 17, p.o. box 42-200 Częstochowa, Poland, e-mail: dc@el.pcz.czest.pl

REFERENCES

[1] Krykowski K., Hetmańczy J., Gałuszkiewicz Z.: Impact of windings switching on torque-speed curves of PM BLDC motor, XXII Symposium Electromagnetic Phenomena in Nonlinear Circuits - EPNC 2012 Dortmund and Essen 2012, pp. 87-88.
[2] Krykowski K., Hetmańczyk J., Gałuszkiewicz Z., Miksiewicz R., Computer analysis of high-speed PM BLDC motor properties, COMPEL - The International Journal for

Computation and Mathematics in Electrical and Electronic Engineering, Volume 30, issue 3, 2011, p. 941-956.
[3] Krykowski K., Silnik PM BLDC w napędzie elektrycznym analiza, właściwości, modelowanie (An analysis of a PM BLDC motor with an electric drive - its properties and modeling), Monografia (Monograph), Gliwice 2011.
[4] Krykowski K., Hetmańczyk J., Gałuszkiewicz Z., Miksiewicz R., Computer analysis of high-speed PM BLDC motor properties, XXI Symposium Electromagnetic Phenomena in Nonlinear Circuits, June 29-July 2, Pula, Croatia.
[5] Gałuszkiewicz Z., Krykowski K., Skoć A., Hetmańczyk J., Rezonans mechaniczny w wysokoobrotowym silniku PM BLDC (Mechanical Resonance in High-speed PM BLDC Motor), Instytut Napędów i Maszyn Elektrycznych 'KOMEL' (Institute of Electrical Drives and Machines 'KOMEL'), Zeszyty Problemowe - Maszyny Elektryczne (Electrical Machines - Transaction Journal), no. 86/2010/123.
[6] Patent 225294, Poland 2016
[7] Application Note. Magnetic Position Sensing in Brushless DC Electric Motors. Honeywell: Sensing and Control [document_50263_1.pdf] – www.honey-well.com/sensing
[8] Hall Effect Sensing and Application. MICRO SWITCH Sensity and Control. – Honeywell. – https:/sensing.honeywell.com/hallbook.pdf
[9] Moroz V., Sensitivity to technological errors in systems for optimal control of permanent magnets synchronous motor / V. Moroz, P. Bolkot, I. Snitkov, K. Snitkov / Mathematical and computer simulation. Series: Engineering. — Kamyanets-Podilsky: Kamyanets-Podilsky National University, 2012. — Vol. 7. — Pp. 140-143. — [in Ukraine]
[10] Gałuszkiewicz Z., Gałuszkiewicz P., Całus D., Szymczykiewicz E., System przetwarzania energii - magazyn energii kinetycznej na bazie silnika PM BLDC (Electrical energy processing system – kinetic energy storage based on a PM BLDC motor), Rozdział w monografii (Chapter in monograph): Możliwości i Horyzonty Ekoinnowacyjności - Zelona energia (Opportunities and Prospects of Ecological Innovation - Green Energy), ISBN 978-83-66017-26-9, 2018, p.104-114.
[11] Gałuszkiewicz P., Praca silnika PM BLDC w zakresie pracy z maksymalnym prądem, w trakcie pracy okresowej przerywanej S3 (PM BLDC performance at maximum current at periodically interrupted operation S3), Przegląd Elektrotechniczny, ISSN 0033-2097, R. 93 NR 6/2017, p. 115-118.
[12] Gieras J.F. Permanent magnet motor technology: design and applications / J.F. Gieras, Third edition. CRC Press. London, New York. 2010. –603 p.
[13] Pyrhönen J. in. Design Process of Rotating Electrical Machines. Design of Rotating Electrical Machines / J. Pyrhönen, T. Jokinen, V. Hrabovcova, John Wiley & Sons, Ltd. 2008. –512 p.
[14] Bolund B. Flywheel energy and power storage systems. / B. Bolund, H. Bernhoff, M. Leijon // Renewable and Sustainable Energy Reviews. –2007. № 11(2). pp. 235-258.
[15] Ahrens M. Performance of a magnetically suspended flywheel energy storage device. / M. Ahrens, L. Kucera, R. Larsonneur // IEEE Transactions on control systems . –1996. № 4(5). pp. 17-188.
[16] Power Electronics / Beacon Power, LLC – 2015.
As of 9 February 2019
[http://beaconpower.com/power-electronics].
[17] Shen J.X. Reduction of rotor eddy current loss in high speed PM brushless machines by grooving retaining sleeve / J.X. Shen , H. Hao, M.J. Jin, C. Yuan // Magnetics, IEEE Transactions on, 49(7). –2013. pp. 3973-3976.
[18] Gilson A. Design of a cost-efficient high-speed high-efficiency PM machine for compressor applications / A. Gilson, S. Tavernier, M. Gerber, C. Espanet, F. Dubas, D. Depernet // In Energy Conversion Congress and Exposition (ECCE), IEEE . – 2015. pp. 3852-3856.
[19] Makarchuk O. V. Additional losses in the stator windings of the high-speed brushless electrical machine with the permanent magnets / O. V. Makarchuk // Scientific Bulletin of National Mining University. – 2016. № 6. pp. 107-113.