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LABORATORY TEST OF SURFACE MOUNTED PERMANENT MAGNET BRUSHLESS MOTOR

BADANIA LABORATORYJNE BEZSZCZOTKOWEGO SILNIKA Z MAGNESAMI TRWAŁYMI MONTOWANYMI POWIERZCHNIOWO

A b s t r a c t

In the paper, the results of laboratory tests of a surface mounted permanent magnet brushless motor were presented. Two power electronics systems, which are made as inverters for PMSM and BLDC motors, were used. The PMSM inverter supplies the motor with sinusoidal currents and the BLDC inverter supplies the motor with trapezoidal voltage. The motor characteristics and its waveforms were determined when the motor was supplied from the BLDC inverter and the PMSM inverter. A comparison of the influence of the motor supply method on its features and parameters was performed.

Keywords: brushless motor with permanent magnets, BLDCM, PMSM, mechanical characteristics, waveforms

S t r e s z c z e n i e

W artykule zamieszczono wyniki badań laboratoryjnych beszczotkowego silnika z magnesami trwałymi montowanymi powierzchniowo. W badaniach zastosowano dwa układy energoelektroniczne, które zostały wykonane jako falowniki do silnika PMSM oraz BLDCM. Falownik PMSM zasila silnik prądami sinusoidalnymi. Falownik BLDCM zasila silnik napięciem trapezoidalnym. Zostały wyznaczone charakterystyki silnika oraz jego przebiegi czasowe przy zasilaniu go jako PMSM oraz BLDCM. Dokonano porównania wpływu sposobu zasilania silnika na jego właściwości i parametry.

Słowa kluczowe: bezszczotkowy silnik z magnesami trwałymi, BLDCM, PMSM, charakterstyki mechaniczne, przebiegi czasowe

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1. Introduction

Brushless motors with permanent magnets are an alternative for other types of electric machines. High-energy magnetic materials used in permanent magnets, e.g. rare-earth elements, allow obtaining very good magnetic parameters [1–7]. Magnets made from NdFeB (neodymium magnets) allow obtaining very good features of brushless machines with permanent magnets, such as high efficiency of energy conversion, very good ratio of the generated torque to the machine volume unit. One method of permanent magnets mounting is fastening them on the surface of a rotor (SPM – surface permanent magnets). The surface mounting method has both advantages and disadvantages. The advantages include: easier shaping of the induced voltage, eliminated reluctance torque, great opportunities of permanent magnet shaping. Surface-mounted magnets also have disadvantages, such as necessity of magnets protection from the centrifugal force, much greater impact of a stator flux on magnets, which leads to greater susceptibility to demagnetizing. In surface mounted magnets, losses from eddy-currents are greater and it is a serious problem. To protect magnets from the centrifugal force, a greater air-gap is required.

Two ways of supplying brushless motor with permanent magnets are possible, regardless of the magnets' mounting method. It depends on the shape of the induced voltage, so brushless DC machines with permanent magnets can be divided into three groups:

– with sinusoidal voltage or close to sinusoidal,
– with trapezoidal voltage or close to trapezoidal,
– with voltage that is not similar to sinusoidal or trapezoidal.

The shape of the induced voltage is important when a method of supplying is selected. In the case of a motor with the trapezoidal induced voltage or close to trapezoidal, the inverter with the trapezoidal voltage is preferred. Theoretically, it is the most optimal solution in the point of view of the generated electromagnetic torque and its ripple.

In the paper, laboratory tests of a brushless motor with surface-mounted permanent magnets with trapezoidal induced voltage were conducted. The motor was supplied from two different power electronics systems, which realize inverter functions for supplying the BLDC motor and the PMSM motor. Identical laboratory tests were conducted in both variants. Line currents of the motor were presented both during no-load operation and under load operation. Standard mechanical characteristics and efficiency characteristics (for various speeds), dynamic characteristics (start-up on no-load and under load, reversal), were determined. It was possible to set the working point in both stationary states and dynamic states. Based on the test results, conclusions concerning possibility of supplying BLDC motor with sinusoidal current were presented.

2. The laboratory setup for tests of brushless dc motor with surface-mounted permanent magnets

In Table 1, parameters of the tested brushless DC motor with surface-mounted permanent magnets are presented.

Table 1

Parameters of tested brushless motor with surface-mounted permanent magnets

Parameters	Value
Supply voltage U_N [V]	3×400
Rated power P_N [kW]	4
Rated stator current I_N [A]	11.5
Rated speed n_N [rev/min]	1500
Number of stator poles *N*s	48
Number of rotor poles N_r	4
Winding type	Distributed
Magnets type	Neodymium

Fig. 1 shows a schematic diagram of the laboratory setup.

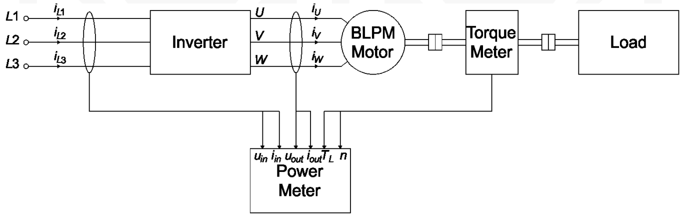

Fig. 1. A schematic diagram of the laboratory setup for tests of brushless motor

In the laboratory setup, Yokogawa WT1600 six-channel digital power meter was used to measure electric parameters (currents and voltages). The power meter was additionally equipped with a motor module, which allows measuring the load torque T_L and speed *n*. The tested brushless motor with permanent magnets was coupled with a DC machine. The torque meter, which was mounted between the DC machine and the tested motor, was used to measure the load torque. Selected waveforms in dynamic states were registered with a four-channel digital oscilloscope. The power meter allows registering waveforms of all parameters (currents, voltages, load torque and speed) only in steady states. Currents and voltages were measured before and after the inverter, which allows determining not only the overall efficiency of the whole drive system, but also the efficiency of the motor and the power electronics system.

Two inverters were used in the tests. Both systems were built based on the Twerd MFC710 vector inverter. One of the inverters was adapted to operation with a brushless DC motor with permanent magnets (BLDC). The second one was designed for operation with a synchronous motor with permanent magnets (PMSM). Both inverters were adapted for operation in the first regulation zone, i.e. with a constant torque. Moreover, inverters were supposed to operate in a closed loop speed control.

3. Waveforms

3.1. Induced voltage

Theoretically, the shape of the induced voltage is very important in terms of supply method selection. Fig. 2 shows the registered waveforms of line-to-line induced voltages of the tested motor at a speed of 1000 rev/min.

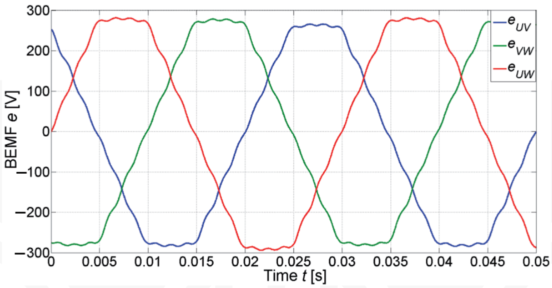

Fig. 2. Induced voltages of the tested motor

The shape of the induced voltage is trapezoidal. Therefore, the tested motor is suitable for supply with trapezoidal voltage (BLDC inverter).

3.2. Waveforms in steady states

Waveforms of currents and voltages of the brushless DC motor were registered without load and under load with $T_L = 20$ N·m at speed $n = 1500$ rev/min. Figs. 3–4 show line currents i of motor during no-load (Fig. 3) and under load (Fig. 4).

Currents are highly distorted, regardless of the supply method during no-load. This is typical for brushless motors with permanent magnets. During operation under load, waveforms of currents seem to be similar to a square wave during BLDC operation (Fig. 4a) and a sine wave during PMSM operation (Fig. 4b). Visible distortions of currents are mainly caused by the speed regulator. The speed regulator controls the instantaneous value of currents to maintain speed on a defined level (by current regulator).

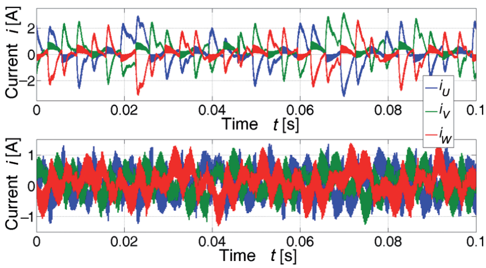

Fig. 3. Waveforms of line currents of the motor at $T_L = 0$ N·m working as: a) BLDCM, b) PMSM

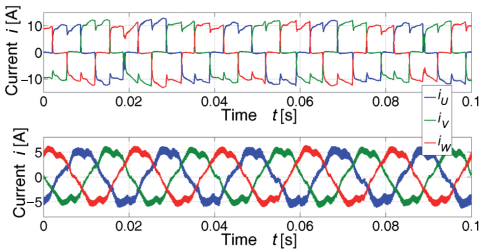

Fig. 4. Waveforms of line currents of the motor at T_L = 20 N·m working as: a) BLDCM, b) PMSM

3.3. Waveforms in dynamics states

Start-up and reversal of the motor was tested in laboratory conditions. Start-up time t_r, braking time t_h and stopping time t_s were possible to be changed in control units of both power electronics systems and they were set up to: t_r = 4 s, t_h = 3 s, t_s = 3 s. Additionally, it was assumed that, during start-up, the motor current can reach 150% of the rated value and the electromagnetic torque can reach 150% of the rated torque.

Two cases were analyzed during tests in dynamic states. In the first one, a separately excited DC generator was not loaded. In the second case, the generator was producing load of the tested motor. Figs. 5–6 show waveforms of speed during start-up without and under load, respectively. Start-up time was set to t_r = 4 s.

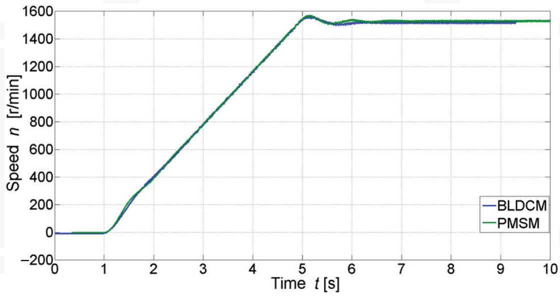

Fig. 5. Speed of the tested motor during the start-up at T_L = 0

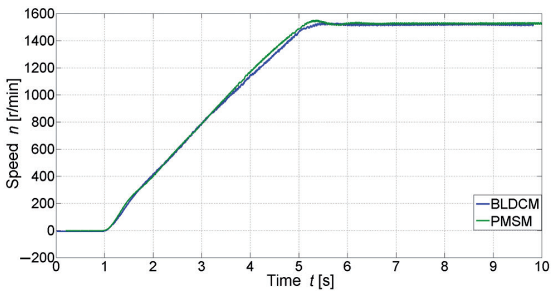

Fig. 6. Speed of the tested motor during the start-up at T_L > 0

Figs. 7–8 show waveforms of the line current *i* of the phase *U* during the start-up

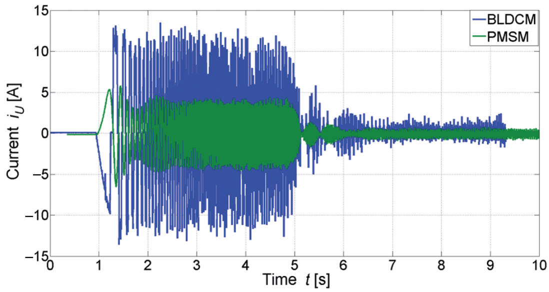

Fig. 7. Waveforms of the motor current i_U of the phase U of the tested motor during the start-up at $T_L = 0$

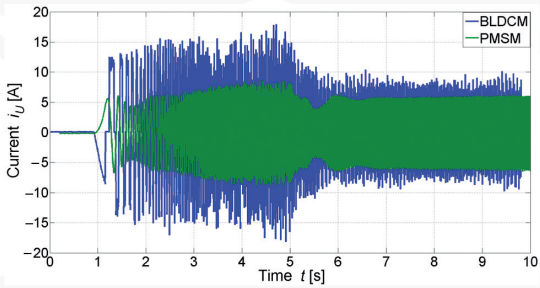

Fig. 8. Waveforms of the motor current i_U of the phase U of the tested motor during the start-up at $T_L > 0$

During the start-up under load, the motor reaches the defined speed in time exceeding 4 s. Both power electronic systems ensure comparable dynamic parameters of the motor. However, during operation as BLDC, a higher value of currents is required. Similar results were achieved during motor stoppage or during reversal. Fig. 9 shows the speed during reversal.

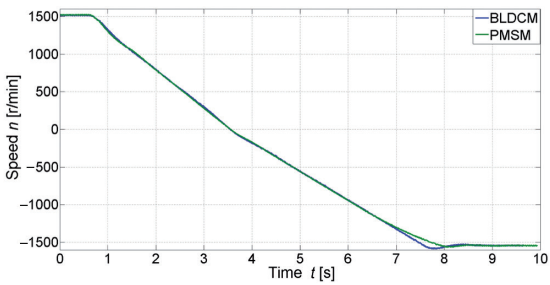

Fig. 9. Speed of the tested motor during reversing at $T_L = 0$

4. Static characteristics

4.1. Test conditions

Laboratory tests were conducted at several values of speed, which were set up in the speed regulator i.e. 250 rev/min, 750 rev/min and 1500 rev/min. The value of the load torque T_L was increased to achieve at least the rated value. Both power electronics systems were forcing operation with constant speed taking into account the limitations of control algorithms.

4.2. Supply from BLDC inverter

Fig. 10 shows speed n in the function of the load torque T_L.

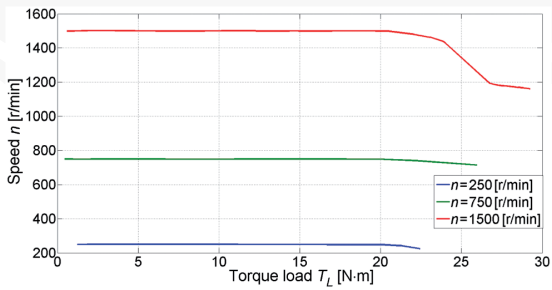

Fig. 10. A dependence of speed n in the function of the load torque T_L during BLDC operation

In the case of BLDC operation, the used power electronics system was not able to maintain a defined speed when the load torque increased over 21 N·m, which in turn caused the motor working point to change. It was noticeably visible at the rated speed (1500 r/min).

Figs. 11–13 show the overall efficiency η (Fig. 11), motor efficiency η_M (Fig. 12) and efficiency of power electronics system η_{inv} (Fig. 13) in the function of the load torque T_L.

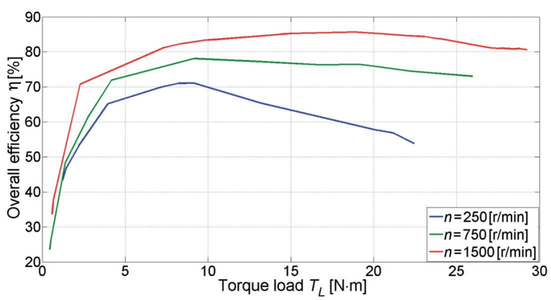

Fig. 11. A dependence of overall efficiency η in the function of the load torque T_L during BLDC operation

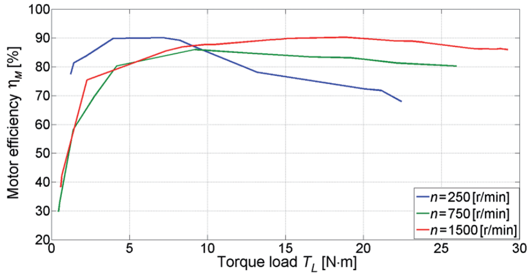

Fig. 12. A dependence of motor efficiency η_M in the function of the load torque T_L during BLDC operation

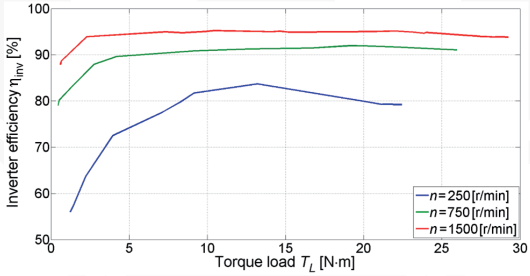

Fig. 13. A dependence of efficiency of power electronics system η_{inv} in the function of the load torque T_L during BLDC operation

The highest efficiency was achieved at rated speed. The efficiency of the power electronics system decreases significantly during decreasing motor speed. Therefore, it has significant influence on the overall efficiency. The efficiency of motor did not exceed 90%.

4.3. Supply from PMSM inverter

The characteristics of the tested motor supplied from PMSM inverter were determined for the same settings of the speed regulator. Fig. 14 shows speed n in the function of the load torque T_L.

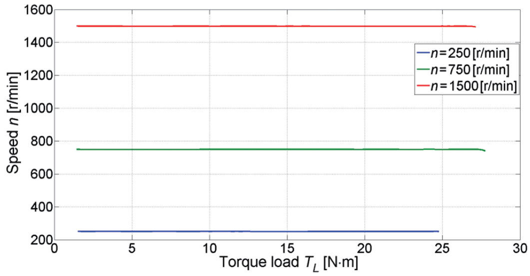

Fig. 14. A dependence of motor speed n in the function of the load torque T_L during PMSM operation

The motor supplied from the PMSM inverter allows obtaining a higher value of the load torque T_L than the rated value at adjusted speed.

Figs. 15–17 show the overall efficiency η (Fig. 15), motor efficiency η_M (Fig. 16) and efficiency of power electronics system η_{inv} (Fig. 17) in the function of the load torque $T_{L.}$

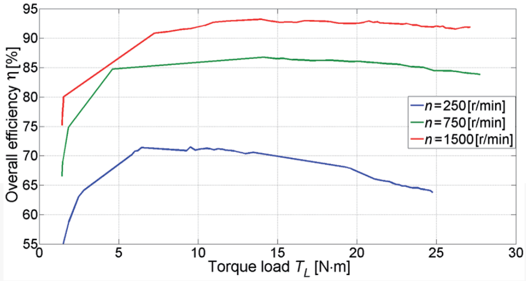

Fig. 15. A dependence of overall efficiency η in the function of the load torque T_L during PMSM operation

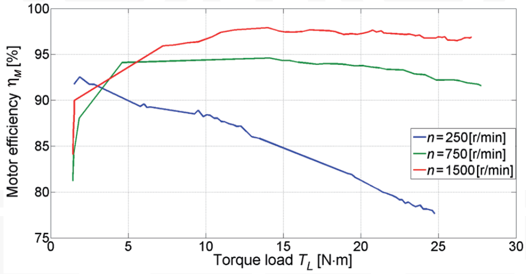

Fig. 16. A dependence of motor efficiency η_M in the function of the load torque T_L during PMSM operation

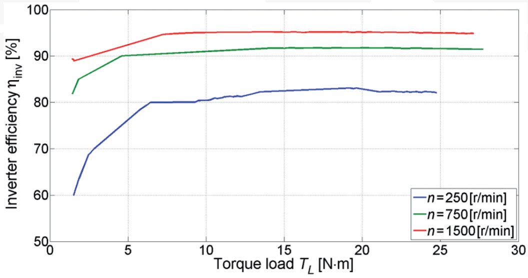

Fig. 17. A dependence of efficiency of power electronics system η_{inv} in the function of the load torque T_L during PMSM operation

The tested brushless motor with permanent magnets during operation as PMSM was reaching higher overall efficiency in the whole speed range.

5. Summary of test results

In table 2, chosen parameters of the tested motor in two variants were set up. In both cases, the load torque equaled 20 N·m.

Table 2

Chosen parameters of the drive for three values of speed during different control methods

	Parameter	250 rev/min	750 rev/min	1500 rev/min
BLDCM	Supply current I_{L1}	3	5.8	9.3
	Motor current I_U	10.7	10.8	10.9
	Overall efficiency η	58	76	86
	Motor efficiency η_M	72	83	90
	Inverter efficiency η_{inv}	80	92	95
PMSM	Supply current I_{L1}	2.7	5.2	8.6
	Motor current I_U	9	9	9
	Overall efficiency η	68	86	92
	Motor efficiency η_M	81	94	97
	Inverter efficiency η_{inv}	83	92	95

The motor supplied from the PMSM inverter ensures higher drive efficiency regardless of the working point. Higher rms phase current is required to obtain the same load torque T_L when the motor is supplied with trapezoidal voltage. It means that the torque constant of the motor, which is supplied with trapezoidal voltage, is lower than of that supplied with sinusoidal voltage (PMSM). Therefore, losses (copper losses, iron losses and also losses in magnets) are higher during supply with trapezoidal voltage. The efficiency of both BLDC and PMSM inverters was comparable. However, the presented results of laboratory tests concern the case when voltage was trapezoidal. When induced voltage will be close to sinusoidal, higher differences between BLDC and PMSM supply should be expected in favor of PMSM. It will be a subject of future research works.

5. Conclusions

In the paper, the results of laboratory tests of a brushless motor with permanent magnets were presented. The tested motor was supplied from two different power electronics systems, which realize inverter functions for supplying the BLDC motor and the PMSM motor. The tested motor has permanent magnets mounted on the surface of the rotor. Simultaneously, the shape of the induced voltage is trapezoidal. Therefore, it prefers this motor to be supplied from the BLDC inverter. However, the conducted tests showed that instead of a trapezoidal shape of the induced voltage, higher efficiency was achieved when the motor was supplied from the PMSM inverter. When the motor was supplied from the BLDC inverter, especially at a low speed, higher ripples were visible, which in turn were not visible when the motor was supplied from the PMSM inverter.

References

[1] Staton D.A., Deodhar R.P., Soong W.L, Miller T.J.E, *Torque Prediction Using the Flux-MMF in AC, DC, and Reluctance Motors*, IEEE Transactions on Industry Applications, Vol. 32, No. 1, 1996, 180–188.

[2] El-Refaie A.M., *Fractional-slot concentrated windings synchronous permanent magnet machines: opportunities and challenges*, IEEE Transactions on Industrial Electronics, Vol. 43, Issue 1, 2010, 107–121.

[3] Gieras J.F., Wing M., *Permanent Magnet Motor Technology – Design and Applications*, Second Edition, 2002.

[4] Tae-Jong Kim, Sang-Moon Hwang, Kyung-Tae Kim, Weui-Bong Jung, Chul-U Kim, *Comparison of dynamic responses for IPM and SPM motors by considering mechanical and magnetic coupling*, IEEE Transactions on Magnetics, vol. 37, Issue 4, 2001, 2818–2820.

[5] Dorrell D.G., Hsieh M.F., Popescu M., Evans L., Staton D.A., Grout V., *A Review of the Design Issues and Techniques for Radial-Flux Brushless Surface and Internal Rare-Earth Permanent-Magnet Motors*, IEEE Transactions on Industrial Electronics, vol. 58, Issue 9, 2011, 3741–3757.

[6] Bianchi N., Bolognani S., Dai Pre M., *Magnetic Loading of Fractional-Slot Three-Phase PM Motors With Nonoverlapped Coils*, IEEE Transactions on Industry Applications, vol. 44, Issue: 5, 2008, 1513–1521.

[7] Wu L., Qu R., Li D., Gao Y., *Influence of Pole Ratio and Winding Pole Numbers on Performance and Optimal Design Parameters of Surface Permanent-Magnet Vernier Machines*, IEEE Transactions on Industry Applications, vol. 51, Issue 5, 2015, 3707–3715.

[8] Korkosz M., Podskarbi G., *Badania laboratoryjne bezszczotkowego silnika prądu stałego z magnesami trwałymi montowanymi powierzchniowo*, Proceedings of Conference on Selected Issues of Electrical Enginereeng and Electronics (WZEE 2016), 4–8.05.2016 Rzeszow, 2016 (in polish).