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SYNCHRONOUS MOTOR PROTOTYPE WITH AN EXTERNAL ROTOR USING PERMANENT MAGNETS

PROTOTYP SILNIKA SYNCHRONICZNEGO Z ZEWNĘTRZNYM WIRNIKIEM I MAGNESAMI TRWAŁYMI

A b s t r a c t

This paper presents the design, simulation and measurement of a synchronous motor prototype with an external rotor using permanent magnets. The motor was optimized for high-torque, in-wheel operation. Based on geometric dimensions, a 3D solid model was created. The electromagnetic design was calculated in ANSYS/RMxprt. A cross-section with graphical presentation of magnetic induction in particular parts of the electromagnetic circuits and the simulated and measured characteristics of the motor are shown.

Keywords: *synchronous motor*, *permanent magnet*, *ANSYS/RMxprt program*

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

W artykule przedstawiono projekt, symulację i pomiar prototypu silnika synchronicznego z zewnętrznym wirnikiem z użyciem magnesów trwałych. Silnik został zoptymalizowany ze względu na wysoki moment do pracy w kole samochodu. Na podstawie wymiarów geometrycznych został utworzony trójwymiarowy (3-D) model silnika. Elektromagnetyczny projekt silnika został obliczony w programie ANSYS/RMxprt. W pracy zaprezentowano przekrój z graficznym przedstawieniem indukcji magnetycznej w poszczególnych częściach elektromagnetycznego obwodu oraz zasymulowane i zmierzone charakterystyki silnika.

Słowa kluczowe: *silnik synchroniczny*, *magnes trwały*, *program ANSYS/RMxprt*

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1. Introduction

Servo drives with permanent magnet (PM) motors fed from static inverters are finding applications on an increasing scale. PM servo motors with continuous output power of up to 15 kW at 1500 rpm are common. Rare-earth PMs have also been recently used in large power synchronous motors rated at more than 1 MW [1]. Synchronous motors operate at a constant speed in absolute synchronism with the line frequency or can also be supplied from a frequency converter. Currently, synchronous electric motors with permanent magnets (PM) and an external rotor are gradually applied in the drives of electric vehicles and are stored directly in the wheel.

Hub motors, also called in-wheel motors, were first patented in the 1880s. In 1899 the Viennese firm of Lohner & Co. built a car powered by battery-driven hub motors. This car was also unique as the world's first front wheel drive system. A news report at the time described the development of the first-ever transmissionless vehicle as a revolutionary innovation. The electric motor in the hubs of the front wheels had an output of 1.8 kW at 120 rpm [2].

2. The synchronous motor with PM external rotor – model and simulation

This chapter presents results of the electro-magnetic proposal for a synchronous motor with external rotor with permanent magnets, simulation of electromagnetic field motor and its operating characteristics. Basic electrical characteristics have been developed on the basis of operational requirements for the motor – these are shown in Table 1.

Table 1

The synchronous motor parameters

Parameter	*Value*
Rated power	3 kW
Rated voltage	3 x 82 V (Y)
Rated current	27 A
Rated torque	38 Nm
Synchronous speed	750 rpm

The electromagnetic design of the motor was calculated and optimized in ANSYS/RMxprt. Based on the required electrical parameters and the geometric dimensions resulting from the motor mount, a 3D model of electromagnetic circuit of the motor was designed in ANSYS/Maxwell (Fig. 1).

The following are simulation results of the synchronous electric motor with an external rotor and PM. The simulation of the electromagnetic field of the synchronous motor with PM is shown in Fig. 2. Figure 3 shows a simulation of the induced voltage in all three phases of the synchronous machine.

The simulation of the motor and load torque is shown in Fig. 4. The speed of synchronous motor was 750 rpm. The simulation of the motor speed and torque is shown in Fig. 5.

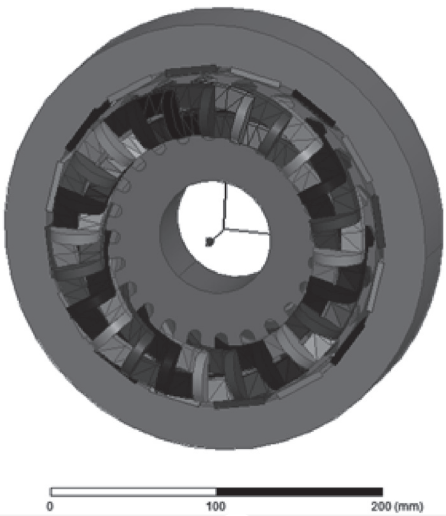

Fig. 1. The 3D model of synchronous motor with PM

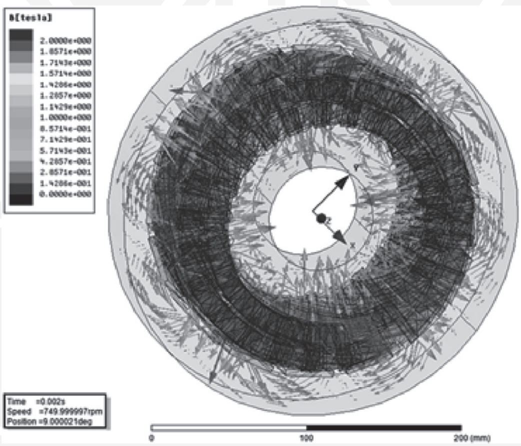

Fig. 2. Magnetic field of synchronous motor with PM

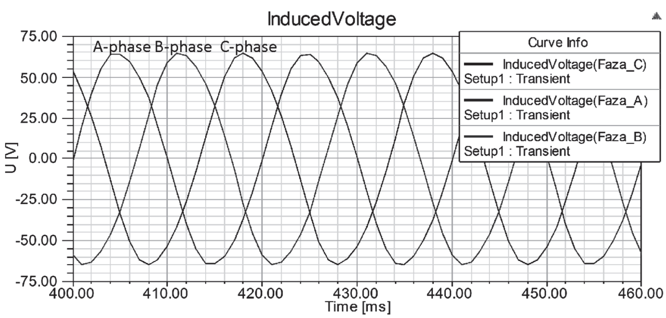

Fig. 3. Induced voltage calculated by ANSYS/Maxwell 3D

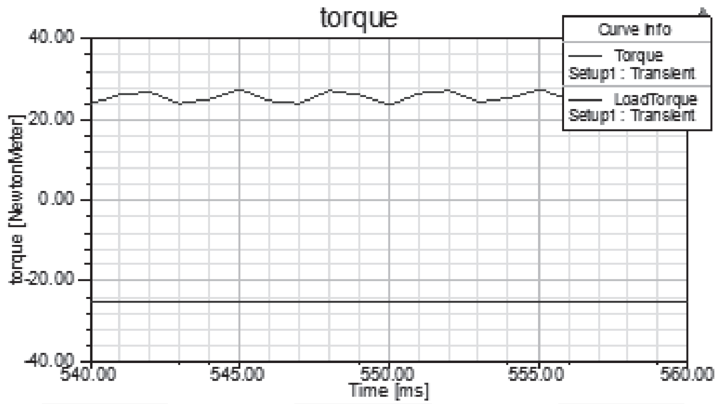

Fig. 4. Simulation of the motor and load torque calculated by ANSYS/Maxwell 3D

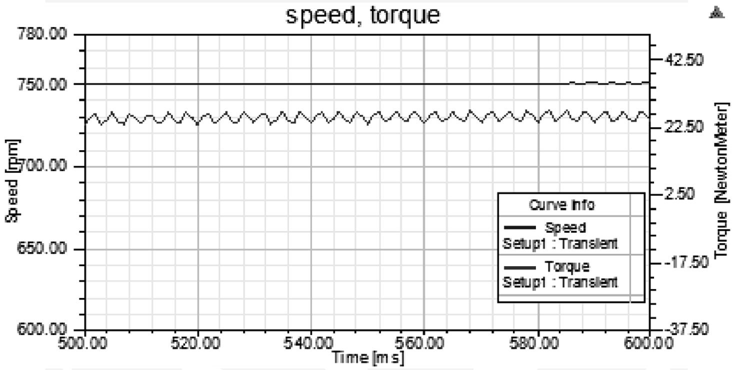

Fig. 5. Simulation of the motor speed and torque calculated by ANSYS/Maxwell 3D

3. Structural design of synchronous motor

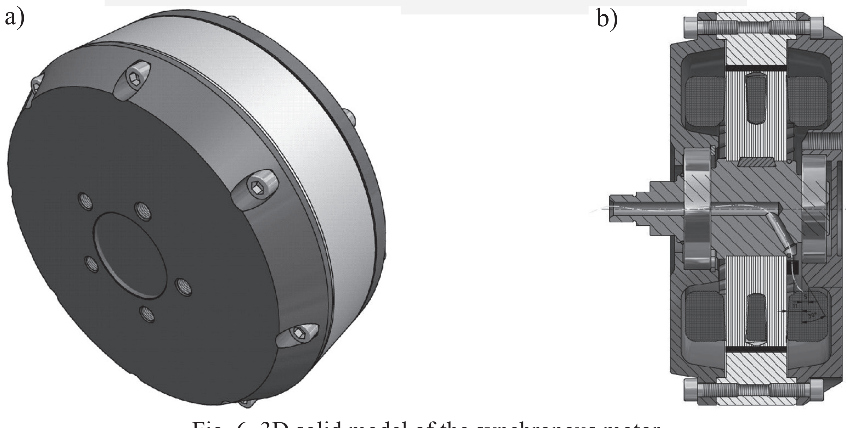

Fig. 6. 3D solid model of the synchronous motor

The construction and external dimensions of the motor are designed so that the motor can be easily positioned and mounted onto a traditional 14” steel rim wheel. The 3D solid model of the stator synchronous motor was created based on the geometric dimensions of the optimized simulation. Figure 6a) shows the general view of the 3D solid model of the synchronous motor with permanent magnets and the inverse rotor. A cross-sectional view of the synchronous motor is shown in Fig. 6b).

4. Measurement of synchronous motor prototype

Based on the structural design of the motor referred to in chapters 2 and 3, a functional prototype was devised. The synchronous motor was used for practical measurements in the laboratory, a photo of which is displayed in Figs. 7 and 8.

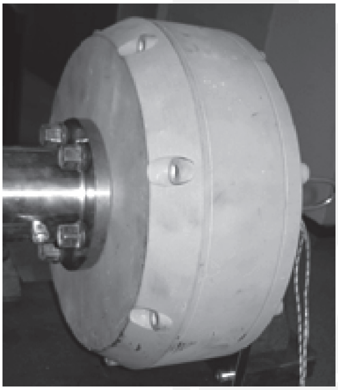

Fig. 7. The synchronous motor prototype

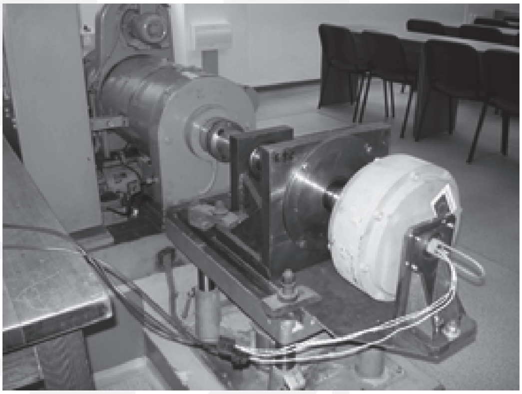

Fig. 8. Measurement of the synchronous motor prototype in the laboratory

4.1. Measurement of generator operation

When measured in a no load generator, the waveforms were recorded with an oscilloscope showing the voltage induced in individual phases. Figure 9 shows waveforms of induced voltages in the phases of the generator at a speed of 750 rpm.

When load is exerted on the generator (resistive load), its terminal voltage drops. In this measurement, the phase voltage reached 47.6 V (RMS) and the line-to-line voltage was 82.6 V (RMS). The frequency analysis of phase voltages (no load generator) is shown in Table 2.

Table 2

Frequency analysis of phase voltages

Order	U1[%H01]	U2[%H01]	U3[%H01]
1	100	100	100
3	2.2	2.2	2.3
5	1.4	1.4	1.5
7	-	0.1	-

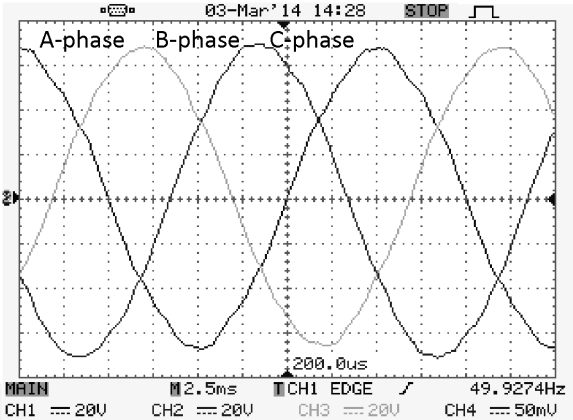

Fig. 9. The measured induced voltages

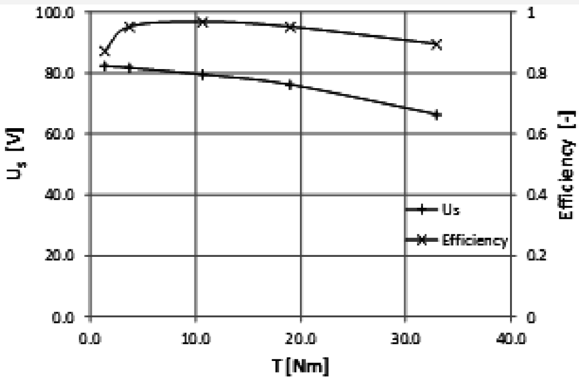

Fig. 10. Measured quantities for loads on the generator

When a load is exerted on the generator (resistive load), its terminal voltage drops. A plot of the terminal voltage and efficiency versus mechanical torque for a generator speed of 750 rpm is shown in Fig. 10. The measured quantities are indicated by crosses. Whilst the average efficiency is 94%, the voltage drop is up to 19%.

Figure 11 shows waveforms of voltage in the first phase and of the load current. The generator is loaded with a constant current of 20 A (RMS). Frequency analysis of phase currents (for load current of 20 A) is shown in Table 3.

Table 3

Frequency analysis of phase currents

Order	I1[%H01]	I2[%H01]	I3[%H01]
1	100	100	100
3	–	–	0.2
5	1.2	1.2	1.2
7	–	0.1	–

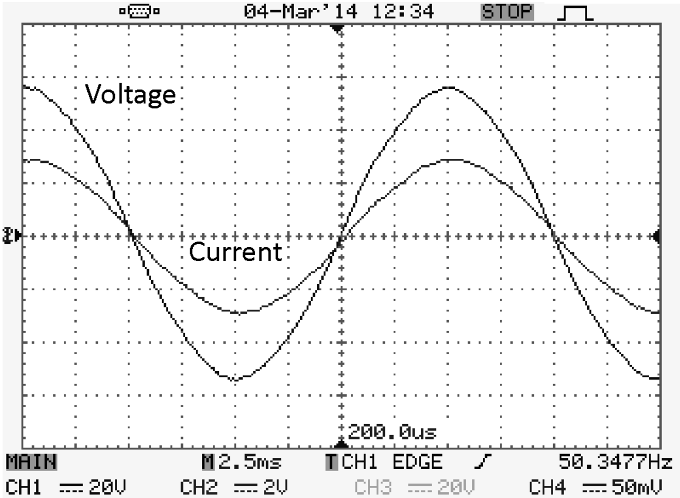

Fig. 11. Measured waveforms of voltage and current

4.2. Measurement of load motor operation

When measuring the synchronous machine in load motor operation, the machine is connected to a rated supply voltage of 82 V (RMS), with a frequency of 50 Hz. During loading of the motor, the supply voltage remains constant.

The synchronous motor was operating at a constant speed (750 rpm) and was loaded by a torque. At a constant mechanical speed, the mechanical output power is equivalent to mechanical torque on the shaft. The plot of motor torque is shown in Fig. 12, the input power and the mechanical power supplied to the rated voltage versus the phase current for a motor speed of 750 rpm. The measured quantities are indicated by crosses.

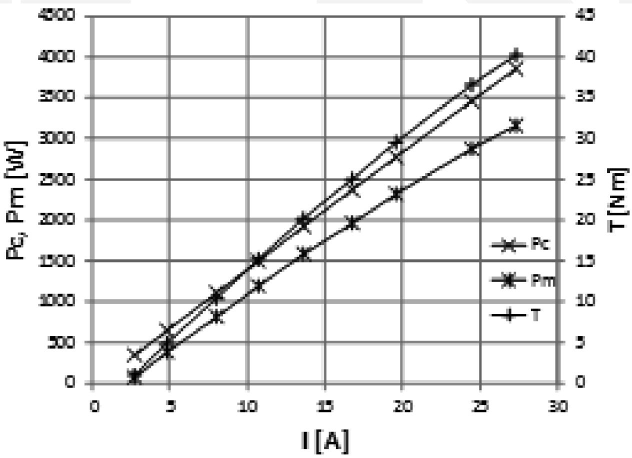

Fig. 12. Measured waveforms of torque and the powers

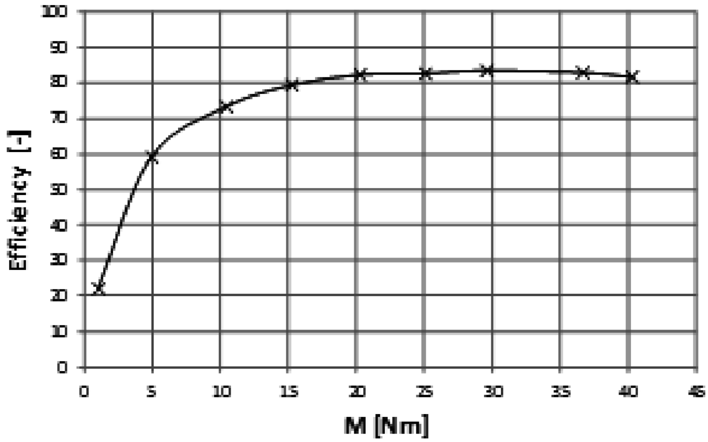

Fig. 13. Measured efficiency of synchronous motor

Figure 13 shows the plot of efficiency versus mechanical torque for synchronous motor speed of 750 and rated supply voltage of 82 V (RMS). The measured quantities are indicated by crosses. Figure 14 shows waveforms of supply voltage in the first phase and current of the motor. The motor is loaded with a constant torque of 1 Nm.

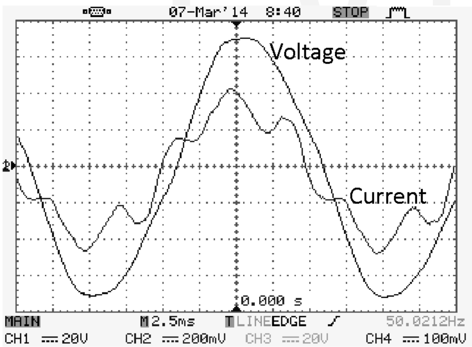

Fig. 14. Measured waveforms of supply voltage and current – *T* = 1 Nm

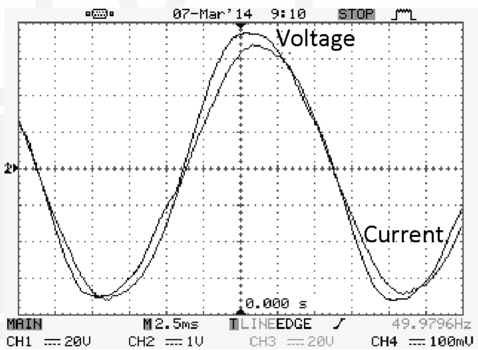

Fig. 15. Measured waveforms of supply voltage and current – *T* = 36.6 Nm

If the motor is loaded with a small torque (*T* = 1 Nm), then the waveform of the motor current contains higher harmonics and is very inharmonic. The motor operates under excitation.

Figure 15 shows waveforms of supply voltage in the first phase and current of the motor, if the motor is loaded with a constant torque of 36.6 Nm and operates as over-excited. If the motor is loaded with a rated torque, then the waveform of the motor current contains lower values of the higher harmonics and is roughly sinusoidal. Frequency analysis of phase voltages (for load motor torque – 36.6 Nm) is shown in Table 4.

Table 4

Frequency analysis of phase voltages

Order	U1[%H01]	U2[%H01]	U3[%H01]
1	100	100	100
3	2.5	2.2	2.0
5	4.2	4.5	4.6
7	1.3	1.8	1.2

Frequency analysis of phase currents (for load motor torque – 36.6 Nm) is shown in Table 5.

Table 5

Frequency analysis of phase currents

Order	I1[%H01]	I2[%H01]	I3[%H01]
1	100	100	100
3	0.6	0.3	0.4
5	1.2	1.0	1.2
7	0.4	0.4	0.5

4. Conclusion

This paper presents initial results of the simulation and measurement of a synchronous machine prototype with an external rotor and permanent magnets. When the synchronous machine works as a generator (resistive load), efficiency is higher than 90%. Efficiency of the synchronous motor is higher than 80% (for load torque higher than 15 Nm). The motor is designed to triple the torque overload. The maximum measured load torque of the synchronous motor was 40.2 Nm. The synchronous motor is designed to withstand three times the torque overload and is intended for in-wheel operation. Therefore, it is anticipated that future measurements will be performed of a synchronous machine supplied with a variable frequency converter.

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