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ANALYSIS OF THE TRACTION DRIVE WORK WITH PERMANENT MAGNET SYNCHRONOUS MOTOR

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The work aims at a discussion of policies and strategies for control and review of the current uses of permanent magnet motor drives for traction in Polish and foreign constructions. As part of this work was a laboratory drive with permanent magnets synchronous motor fed by frequency converter described and reviewed. The laboratory tests, present the characteristics of the drive permanent magnet synchronous motor which shows that the discussed drive is fully suitable for traction applications.

1. INTRODUCTION

Currently PMSM (Permanent Magnet Synchronous Motor) is becoming increasingly interesting for the engineers. Today's dynamic development of materials engineering, and most of all magnetic materials and semiconductors used in power electronic converters, and the development of control algorithms allow to look again at the synchronous machines.The decrease in prices of these materials greatly contributes to the use of permanent magnets in the industry. There has been a fivefold decrease in the cost of the rare-earth magnets the past fifteen years, while the power generated by these magnets has tripled – Fig. 1. [1]. For several years there have been visible attempts to implement on a mass scale PMSM, which is mainly ldue to the best parameters of these machines.

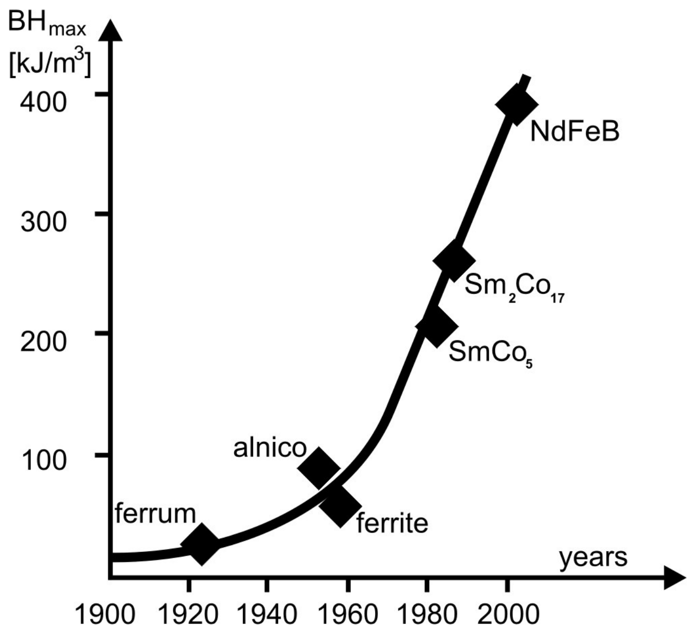

Fig. 1. Permanent magnets development, [2]

The comparison of the properties of three drive motors used in electric traction: series motor, induction motor and PMSM are presented below. The following types of traction machine were used:

1. Lda-327 (U = 250 V, P = 45 kW, m = 645 kg) [3],
2. STDa 200-L4 (U = 380 V, P = 50 kW, m = 280 kg) [4],
3. PMPg-250L (U = 250 V, P = 60 kW, m = 527 kg) [3].

Table 1. Comparison of motors with similar power parameters

Parameter	1	2	3
	series motor DC	induction motor AC	PMSM AC
power density [kW/kg]	0,07	0,18	0,11
torque overload	-	2,0	2,95
cos φ	-	0,92	0,95
commutation	mechanical	electronic	electronic
efficiency	87%	96%	95%

It follows that the PMSM is characterized by a relatively small mass with heavy torque overload and high rate of cos φ (important for high-power engines such as in locomotives).

2. APPLICATIONS REVIEV

Currently in Poland only two companies have decided to apply the PMSM in rail vehicles. The first of them - KONSTAL ALSTOM, has applied these motors in the tram X04. This vehicle is a prototype construction. At the end of 2008, one copy was imported from France ALSTOM factory to Katowice, where it was tested on the section Chorzow - Katowice, Fig. 2. KONSTAL ALSTOM representatives assure that the mass production in Chorzów factory will start soon, [5].

This tram is a construction designed for the needs of Central and Eastern Europe market . It manifests in a large share of steel elements in the construction of the vehicle body. Engineers from Central and Eastern Europe rely more on steel than on the more expensive modern aluminum alloys commonly used in the construction of bodies for rolling stock in the western part of the continent. There are no generally available specifications of this vehicle and company representatives are not willing to share the data, which makes it impossible to evaluate the applied drive characteristics. This can be explained by the fear of using innovative solutions by other companies not a single vehicle of this type has been purchased by the Polish urban transport company up till now.

Fig. 2. ALSTOM X04 prototype tram in test run on the streets of Katowice [6]

The second company which implements PMSM in rail vehicles is Research and Development Centre of Electrical Machines KOMEL in Katowice (Branżowy Ośrodek Badawczo-Rozwojowy Maszyn Elektrycznych KOMEL w Katowicach).

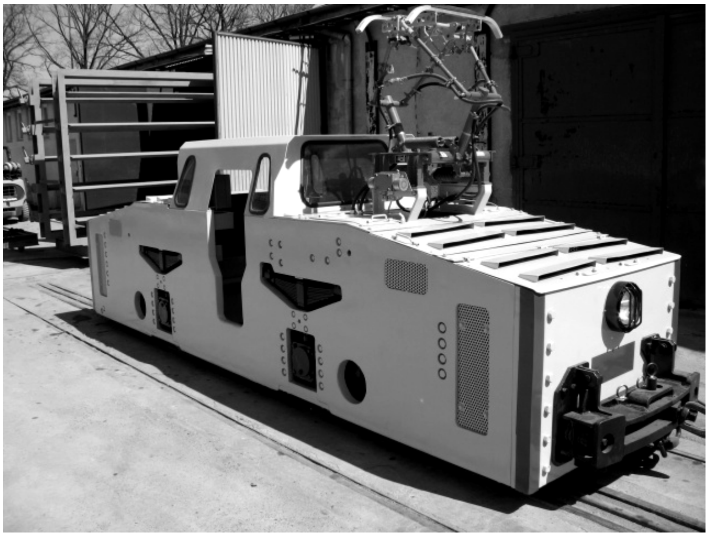

Fig. 3. Mining locomotive Ld-31 EM with PMSM produced by Komel [7]
The company exists since 1948 as an independent testing center and builds its own prototypes, and is ready to apply traction drives, Fig 3 and 4

Fig. 4. Locomotive Ld-31 EM, control panel, [7]

KOMEL designed, built and implemented a prototype drive for the normal operation of mining electric locomotives Ld-31 EM designed to work in underground transport of coal, ore and salt in the mines non-endangered by explosion of methane and / or coal dust. These locomotives are powered by modern PMSM, which significantly contributed to improving the operational performance of locomotives, including an increase in the tractive force, [7]. Adjusting the speed and changing the direction are carried out through an electronic power converter.

Main circuits are powered by voltage 250V DC from traction network, control circuits, lighting and diagnosis 12V DC from traction network through a converter or from the battery. This, In addition to the local control allows for remote control of radio stations in use within the loading or on wagon tippler. Diagnostics (monitoring and recording the basic parameters) was based on a microprocessor device PUL-02. Ld-31EM locomotive is the first vehicle of PMSM using rail traction drive constructed entirely by the Polish research center. Currently KOMEL offers 28 different types of PMSM with power ratings of 1.4 - 60 kW, speeds 750 - 7000 rpm and torque 3.9 - 620 Nm.

In February 2008 the ALSTOM group in France presented the first prototype train AGV (Automotrice á Grande Vitesse) [8], Fig. 5. The train is high-speed electric multiple unit in which the essential element PMSM drive system are - the same who in 2007 helped to beat the current rail speed record - 574.8 km/h, [9].

Fig. 5. AGV electric multiple unit, produced by ALSTOM, [8]

The train has been built since 1998. In November 2005, ALSTOM unveiled the first visualization of the train, and in less than a year later started the production of the first components. Test ride on 3 April 2007 (beating the speed record) related to the TGV, but a large proportion of components in the propulsion system and steering of the project came from the AGV. After the official presentation of the factory in La Rochelle (February 2008) the train was taken to the test track in Velim in the Czech Republic. Since then, the ALSTOM group has not published further information on the status of the project. Advancement of the project and achievements during the first test run show that if the company decides onthe implementation of the regular production, the train will be one of the most modern trains in the world. The use of the PMSM unit led to beating speed record, and therefore is a promising alternative to the induction motors. Unfortunately, dictated by market considerations, the lack of detailed technical information about this innovative solution does not allow for a more accurate analysis of the problem.

On the basis of the review it can be concluded that PMSM is currently used in the few practical solutions. All publications reported present use of PMSM as the best alternative to currently used machines. Among others, the following advantages should be mentioned:
1. Very favorable power density,
2. The simplicity of the engine’s construction
3. Silent running,
4. Durability,
5. High efficiency,
6. Possibility to achieve large values of torque make it less necessary to use reduction gearing,
7. Large motor overload.

All of the above characteristics result from the construction of PMSM. The list contains real advantages but also disadvantages (such power is gained only several years after the implementation of these motors for normal operation), and the feedback of users and designers.

3. LABORATORY TESTS

3.1. Test drive

The studies used the synchronous motor produced by SIEMENS of type 1FT6021-6AK71-1TH0 for:
• rated torque Mn = 0.3 Nm
• rated speed Nn = 6000 rpm
• ated current In = 1,1 A ???
• and voltage Uin = 123 V

It is addressed to driver family MASTERDRIVES MC 6SE7011-type 5EP50 connection PLC which is the converter AC / AC.

This driver uses a vector strategy work while maintaining constant power angle δ = π / 2, so the current regulation component Iq and Id, for which the angle between the rotor magnetic flux vector and the net force is the stator current vector angle, [10].

For the equations of the electromagnetic torque as below:

$$M_e = \frac{3}{2} p \Psi_s I_s \sin \eta \tag{1}$$

$$M_e = \frac{3}{2} p \Psi_f I_s \tag{2}$$

$$\Psi_f = \Psi_s \sin \eta \tag{3}$$

$$M_e = \frac{3}{2} p \Psi_f I_s = k I_s \tag{4}$$

where:
I_s – resultant stator current,
Ψ_f – magnetic flux of rotor (const., permanent magnet),
Ψ_i – magnetic flux of stator,
Ψ_s – resultant magnetic flux,

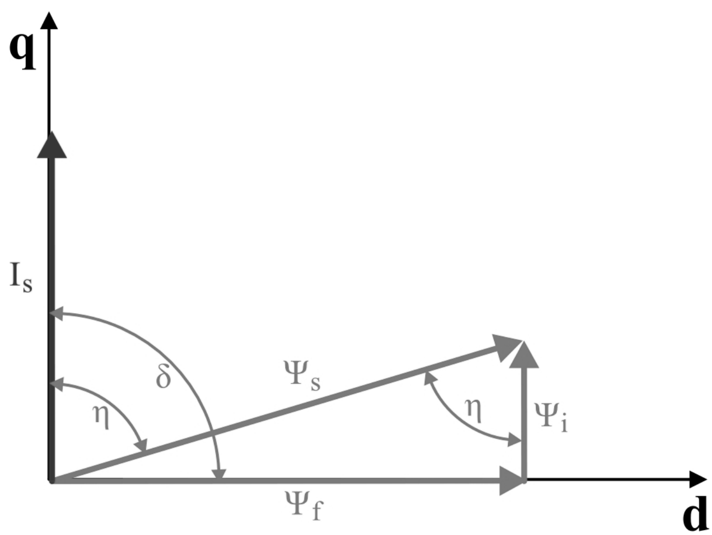

Fig. 6. Vectors of current and magnetic flux of the control strategy for δ = π / 2 [10]

this strategy is shown in Fig. 6.

It can be concluded that for the control strategy δ = π / 2 electromagnetic torque of the motor is directly proportional to the stator current.

During the tests a series of trials were carried out for mechanical characteristics and efficiency of the system.

3.2 Results

The study determined mechanical characteristics of the three-speed fixed n = 100, 1000, 2000, 3000 rot / min. The measurement was carried out bringing the motor idle speed and the chosen burden gradually increasing its shaft torque, Fig. 7.

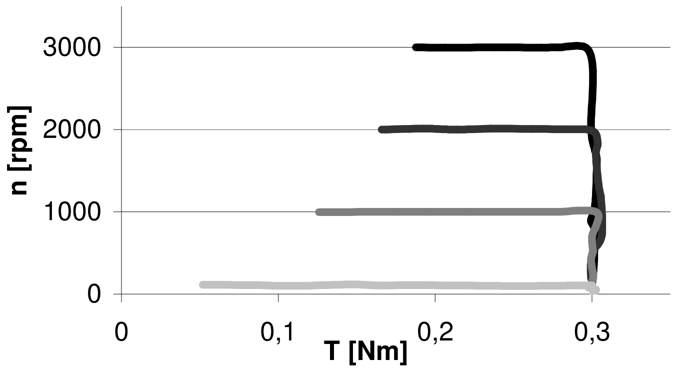

Fig. 7. Mechanical characteristics of the drive [11]

Based on a series of trials involving the registration of start-up, work setting and stopping, for different maximum torque loads equal to 0.3 and 0.6 Nm set efficiency characteristics – Fig 8.

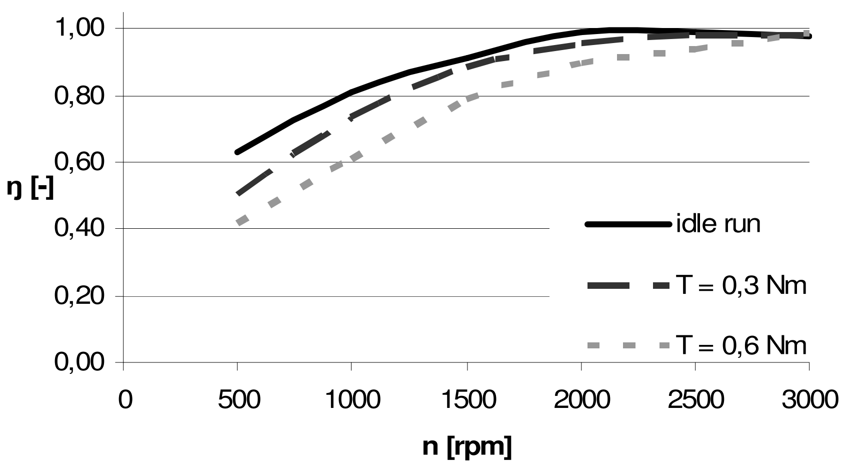

Fig. 8. Efficiency characteristics of the drive [11]

According to the equations (1-4) the dependence of the torque on the stator current is linear – Fig. 9. This greatly simplifies the automatic control.

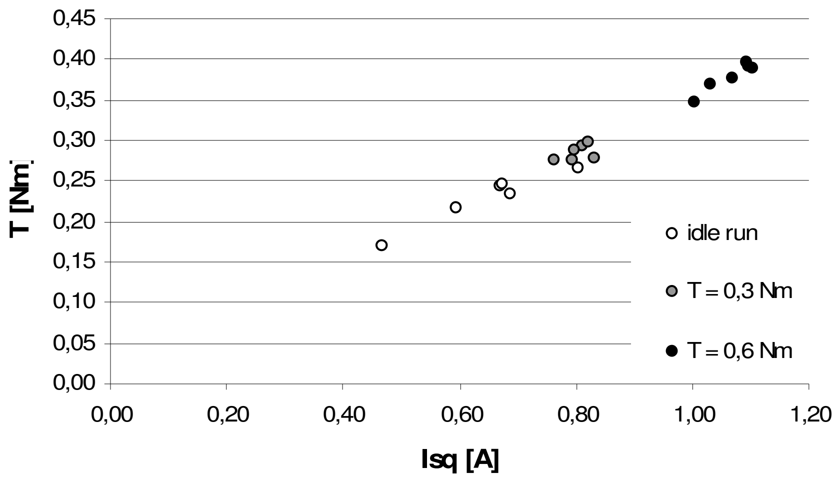

Fig. 9. Torqe T(Isq) function [11]

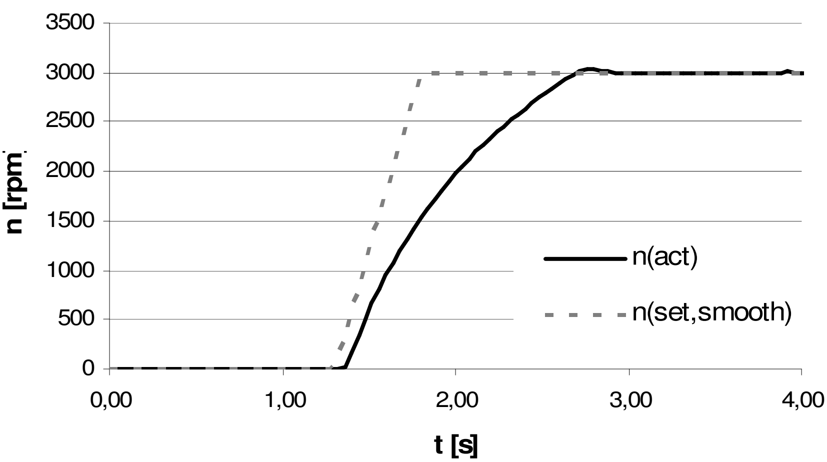

Fig. 10. Starting the PMSM to 3000 rpm [11]

During start-up it found a stable operating mode. The difference in speed of rotation of the stator magnetic field and the rotor exceeded 205%, [11]. Nevertheless, the PMSM continues to work synchronously – Fig. 10.

4. CONCLUSIONS

The drive with PMSM examined in this work is characterized by high efficiency at high speed values Assuming an appropriate choice of the traction engine, the statistically most common speed of the vehicle drive can be obtained with relatively low energy consumption. Given the current trends in the design of traction drives it is essential.

The resultant characteristic fits perfectly to the key assumptions of the drive traction and provides a full fitness test drive for traction applications. Drive rigidly maintains the set speed until the critical torque is reached
With increased load (T = 0.6 Nm) an excessive rise in the temperature of stator windings occurs. This phenomenon can be reduced by forced water-cooled stator windings, which leads to even greater overload of the drive used (with appropriately designed in terms of endurance: shaft, bearings and machine body).

However, the increasing load decreases the efficiency of the engine torque, reserve is sufficient for less frequent overloading (for example, the start-up period), and not for continuous operation (ride the train with a constant speed). the type of vehicle (train hasty, cargo - relatively short compared to the constant speed work, suburban train, tram, metro - a relatively long time from start to constant speed) should also b taken into account.

Satisfactory power to weight ratio for this engine is approx. 0.1 kW / kg, and for more powerful machines it is even 1 kW / kg [8] what encourages to mount the motor in railway traction vehicles directly on the axle of the vehicle, without mechanical gears. In case of direct mounting of the axle set to the engine drive shaft, the small mass of a PMSM, similar to the weight of gear, does not cause a significant increase in undamped weight disadvantage.
Eliminating the gear axis will increase the efficiency of the system, and eliminate the operating costs of mechanical drive. The above-mentioned conditions are beneficial to undertake design work on the prototype drive train with the PMSM fastened directly to the drive shaft wheelset.

This drive served as a research model of reference for high power traction motors from several hundred to several thousand times greater, and therefore the results may not take into account developments in high power drives.

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ANALIZA PRACY NAPĘDU TRAKCYJNEGO Z SILNIKIEM SYNCHRONICZNYM Z MAGNESAMI TRWAŁYMI

Streszczenie

Obecnie coraz większą uwagę konstruktorów elektrycznych napędów trakcyjnych przyciągają silniki synchroniczne z magnesami trwałymi. W artykule opisano obecne osiągnięcia w dziedzinie wdrożeń silników synchronicznych do napędów trakcyjnych oraz przedstawiono wyniki badań laboratoryjnych napędu z silnikiem synchronicznym z magnesami trwałymi współpracującego z przemiennikiem częstotliwości. Omówiono uzyskane charakterystyki oraz przedstawiono zalety tego typu napędu w zastosowaniach trakcyjnych.

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