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Drive system with permanent magnet synchronous motor dedicated to electric platform tractor

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Abstract

The paper deals with a prototype of modern electrical drive system dedicated to all-electric battery-powered platform tractors which currently are being modernized in Poland. In the old drive solutions for this application the DC series motors were used. The main disadvantages of old drive solutions are very low efficiency, usually below 80 % and high DC motor maintenance costs resulting mainly from the existence of brushes and mechanical commutator . The modernized platform tractor will be equipped with the Interior Permanent Magnet Synchronous Motor (PMSM) with inner rotor and sinusoidally distributed stator winding. This PMSM will be supplied by the voltage source inverter. The construction and performance parameters of newly designed prototype of PMSM are described. The main goals of modernization are to increase the efficiency of electric drive and to decrease the down-time, maintenance and repair costs required by electric drive in platform tractor. It was assumed that the battery packs and driving (rear) axle used in modernized platform tractors will be exactly the same like in old tractors.

Keywords: BEV, brushless motor, permanent magnet motor, DC motor

1 Introduction

Electric platform tractors with rechargeable battery packs have been manufactured in Poland since early 1970's (Fig. 1). These platform tractors are equipped with a DC series motor, that means with field winding and armature winding connected in series. The main performance parameters of these tractors are as follows:

- Carried load capacity 2000 kg;
- Weight (with battery) 1600 kg;
- Maximum travel speed with load: 13 km/h (2 x 2.5 kW drive), 15 km/h (5.3 kW drive);
- Maximum travel speed without load: 17 km/h (2 x 2.5 kW drive), 20 km/h (5.3 kW drive);
- Maximum drawbar pull without carried load 3.5 kN;
- Rated drawbar pull without carried load 0.9 kN.

Two versions of electric drive can be met in these old constructions of platform tractors. In the first version, two DC series motors are used with rated power 2.5 kW (30 minutes rating) per motor, rated speed 1000 rpm, rated voltage 80 V, rated current 40.6 A and rated efficiency $\eta = 0.77$. These DC motors are totally enclosed, not ventilated motors (TENV). Weight of each motor is 60 kg. The transmission gear ratio in this version of drive is 7.6. The platform tractor drive with two DC motors is shown in Fig. 2.

Figure1: Battery-powered platform tractor manufactured in Poland since beginning of 1970's

In the second version of electric drive one DC series motor is used with rated power 5.3 kW (60 minutes rating), rated speed 2200 rpm, rated voltage 80 V, rated current 80 A and rated efficiency $\eta = 0.83$. This DC motor is totally enclosed, blower cooled motor (TEBC). Motor weight is 56 kg. Transmission gear ratio in second version of drive is 11.75.

Figure2: Two DC series motors installed in one of the old solutions of electric drive for battery-powered electric platform tractor manufactured in Poland

So-far manufactured platform tractors are equipped with lead-acid battery packs with liquid electrolyte. The main technical data of battery packs installed in these platform tractors are as follows:

- 40 cells type 4A240, nominal cell voltage 2V;
- Nominal battery pack voltage 80 V;
- Rated capacity 240 Ah/5h (240 Ah/5h);
- Weight with electrolyte 690 kg.

The main disadvantages of DC series motors are very well known:

- Because of the mechanical commutator with brushes required by the construction of these motors, the costs of electric tractor maintenance and repair are relatively high;
- Ratio of rated power to motor mass or volume is poor;
- Efficiency of brushed DC motors is very low comparing to other types of electric motors and as the result the maximum range of tractors (given in km) on one battery charge is additionally limited.

The most important disadvantage of DC series motors used in platform tractors is very low efficiency, typically between 0.77 and 0.85.

Figure3: Lead-acid battery pack used in electric platform tractors, nominal battery voltage 80 V

2 Project goals and objectives

The goals of a project are to increase the reliability of electric drive dedicated to battery-powered platform tractors, to decrease the time required for maintenance, to decrease the costs of maintenance and to increase the efficiency of drive.

Two main assumptions were made regarding the modernization of platform tractors. The first one is that the battery packs used in modernized tractors should be left without any changes. This results from relatively very high prices of modern lithium-polymer battery packs and from the fact, that in the case of using the lithium based battery packs it would be required for most of customers to invest in the new charging systems. According to that assumption, the modernized platform tractors will be still equipped with traditional lead-acid battery packs with nominal voltage of 80 V.

The second assumption is that in the modernized tractors the driving (rear) axle and the transmission ratio will be identical to those used in the so-far manufactured tractors equipped with one DC series motor (5.3 kW), to keep the costs of modernization as low as possible.

Taking into account the above assumptions, all the goals of the project can be met by realization of just three objectives. These objectives are to choose a new type of electric motor without brushes and characterized by possibly high efficiency, to design a chosen type of motor in accordance to the requirements of application and to choose and implement in software a motor control algorithm appropriate for a given motor type and application requirements.

3 Conception of electric drive for modernized platform tractors

The most efficient electric motor type available currently for use in all-electric vehicles is Permanent Magnet Synchronous Motor (PMSM) [1]. The main advantages of these motors are:

- The highest efficiency comparing to any other type of rotating electrical machines;
- High rated torque or power achieved from the unit mass and volume;
- High max. to rated torque ratio possible (high torque overload capability) depending on motor construction and inverter parameters;
- High starting torque (max. torque is achievable at zero speed (standstill));
- High reliability (correct design required);
- Air cooling of PMSM is more efficient comparing to DC series motors and AC induction motors as most of power losses in PMSM are located in the stator (assuming inner rotor construction).

It was decided that in the prototype of modernized tractor the PMSM with inner rotor will be used. With regard to mechanical construction of rotor PMSMs can be divided in three main groups:

- Surface Mounted PMSM;
- Inset PMSM;
- Interior PMSM.

With regard to stator winding construction PMSMs can be generally divided as:

- Motors with sinusoidal distributed windings;
- Motors with concentrated windings (non-overlapping, frictional slot windings).

For the prototype of modernized tractor the Interior PMSM with sinusoidally distributed stator winding has been designed.

Interior PMSMs can develop higher values of nominal and maximal torques comparing to other variants of these motors. The reason for this is that in the case of Interior constructions the synchronous torque developed by motor has two components: magnet alignment torque and reluctance torque and these torque components are acting together, increasing the resultant synchronous torque [2, 3].

It was assumed, that the performance of modernized tractors regarding maximal speed and maximal drawbar pull should be the same as in the case of old DC drive solutions, eventually improved, but the efficiency of drive should be higher.

4 PMSM dedicated to modernized platform tractors

The main technical data of PMSM designed for modernized platform tractors are as follows:

- Construction type: Interior PMSM with inner rotor and sinusoidally distributed winding;
- Frame size (shaft height) 132 mm;
- 6-poles construction;
- Core length 120 mm;
- Magnets type: NdFeB (material N33SH);
- TENV construction (water cooling of prototype motor is possible if necessary, for example in other variable speed applications);
- Motor weight 48.5 kg.

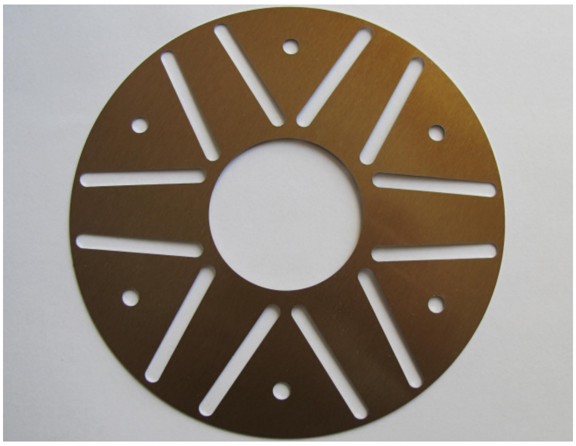

Figure4: Rotor lamination used in the prototype of Interior PMSM dedicated to platform tractor

NdFeB magnets inside the rotor are arranged in a V-shape (Fig. 4) and thanks to this arrangement

the so called air-gap flux concentration is achieved. High value of no-load flux density in the air-gap has positive effect on rated and maximum torque values and motor efficiency.
Prototype Interior PMSM is supplied by voltage source inverter. Inverter type SKAI 4201MD20 form Semikron with 200 V MOSFET transistors was chosen. The maximum operating DC link voltage for this inverter is 160 V, and the maximum allowable AC current ($t < 20$ sec.) is 420 A_{RMS}. Continuous AC current is 370 A_{RMS}. During laboratory tests of prototype electric drive max. inverter current was limited to 350 A_{RMS}.

Figure5: Inverter type SKAI 4201MD20 (Semikron) with 200 V MOSFETs

Usually it is very difficult to meet the torque and speed requirements of electric drive for EV without involving the flux weakening technology [4 ÷ 6]. But it was possible in the case of electric drive for modernized platform tractors.
Maximum drawbar pull required by this application is 3.5 kN. Taking into account the tractor tires diameter (640 mm) and the given transmission gear ratio (12.75), the required torque on Interior PMSM motor shaft is about 90 N.m. Calculated maximum torque (short time overload torque) for prototype electric drive is 105 N.m. This maximum torque is limited by inverter maximum allowable AC current (350 A_{RMS} assumed during tests) and by the chosen motor cooling method (TENV). In fact the prototype motor was not only designed for application in platform tractors and its max. torque capability is much higher.
Maximum travel speed of platform tractor should be 20 km/h. At this travel speed the rotational speed of rotor in Interior PMSM is about 2100 rpm. Even at 2400 rpm and assuming that motor develops maximum torque 105 N.m, the rms line to line voltage on prototype motor terminals is not higher than 45 V. Minimum allowable DC link voltage for these excessive motor operating conditions is about 74 V.

The maximum torque and speed requirements of prototype electric drive for platform tractors are met without the need for flux weakening.

5 Results of laboratory tests

Prototype electric drive with Interior PMSM operating as TENV motor was laboratory tested (Fig. 6). In Fig. 7 the results of thermovision measurements are shown. Photo was taken at the end of load test (temperature rise test) with load torque 35 N.m. Load test was 4 hours long because one of the targets was to check the quality of permanent magnets. At the end of load test the maximum temperature on motor frame was 76.5 °C (170 °F) and the end-winding temperature was 110.6 °C (231 °F). Motor winding has insulation class F, so the maximum operation temperature allowed for this winding is 155 °C (311 °F). Motor frame temperature is uniformly distributed on the frame length (Fig. 7).

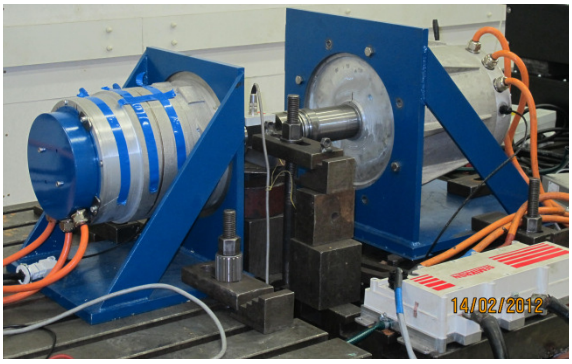

Figure6: Prototype Interior PMSM (on the left side) dedicated to electric platform tractor on the test bench. The blue tapes on the motor frame were required for thermovision measurements

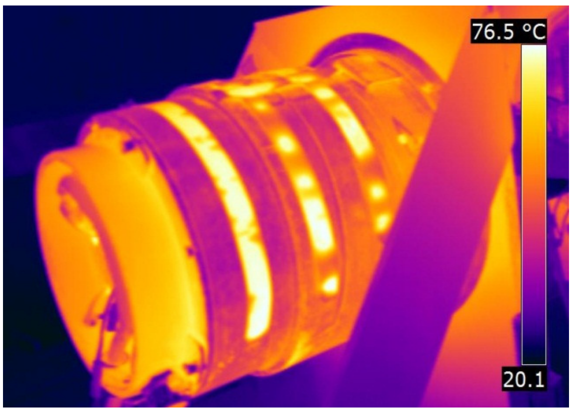

Figure7: Thermovision measurements of prototype Interior PMSM during temperature rise test with shaft torque 35 N.m. Photo taken at the end of test. Max. temp. on motor frame was 76.5 °C and the end-winding temp. was 116 °C. Motor operating as TENV.

In Fig. 8 ÷ 10 the efficiency maps obtained from laboratory tests of prototype drive are presented. Because of test bench constraints, efficiency maps were measured for a range of torques limited to 90 N.m.

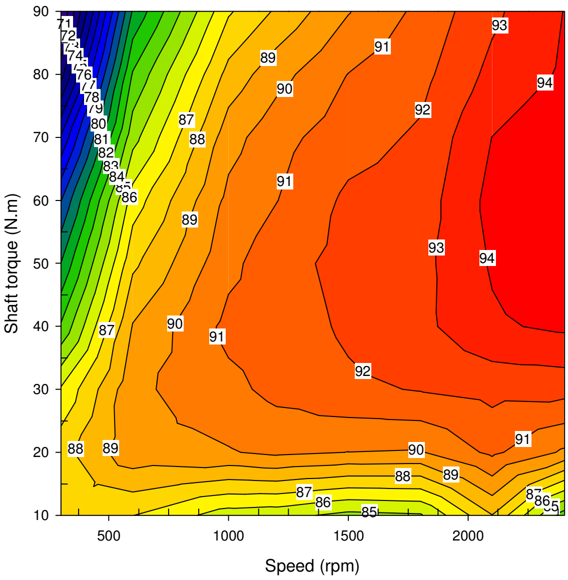

Figure8: Efficiency map of Interior PMSM dedicated to modernized electric platform tractor

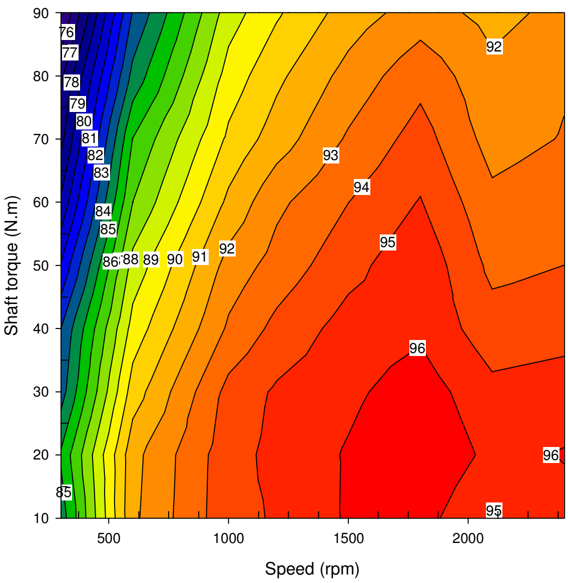

Figure9: Efficiency map of SKAI inverter used during laboratory tests

It can be seen, that prototype motor has efficiency over 90 % in most of operating points. Assuming that the rated travel speed of modernized platform tractor is the same as the rated travel speed of tractor with 1 x 5.3 kW DC motor, that means 15 km/h and about 1600 rpm on motor shaft, and assuming that the rated torque is also the same for both of tractors, that means 23 N.m, the rated efficiency of prototype Interior PMSM is 92 %. For the same rated conditions the efficiency of inverter is about 96 % and the efficiency of complete modernized electric drive is over 88 %. Maximum motor efficiency is slightly over 94 %.

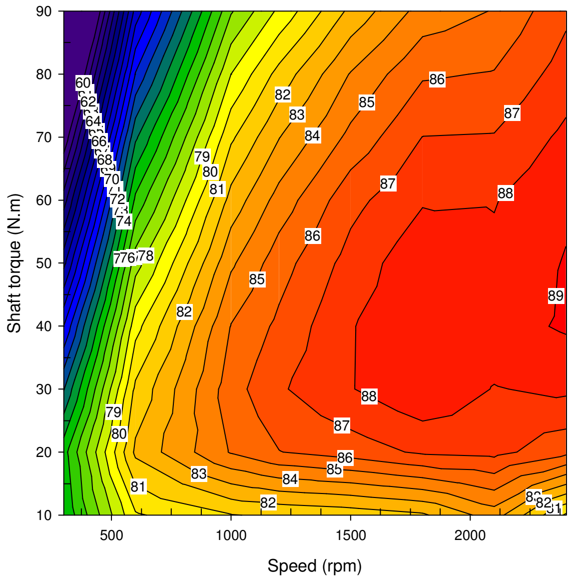

Figure10: Efficiency map of prototype electric drive (motor + inverter) dedicated to modernized electric platform tractor

Rated efficiency of 5.3 kW DC series motor used in old tractor constructions is 83 % and the efficiency of DC series motor controller type ZAPI H2 400A 80V can be predicted as 95 %. Rated efficiency of this old electric drive solution (DC motor + controller) is below 79 %. The new electric drive solution with Interior PMSM to modernized platform tractors has almost 10 % higher efficiency. For operating points other than rated, the difference in efficiency can be even higher for the benefit of the new electric drive.

6 Conclusion

The prototype solution of electric drive dedicated to battery powered electric platform tractors has significantly higher efficiency in the entire range of travel speeds comparing to previous drive solutions based on the DC series motors. At the rated operating conditions the efficiency of modern variable speed drive is almost 10 % higher. In the new drive solution the Interior PMSM is used, supplied by the inverter with output voltages generated as the space vector modulated PWM waveforms. It was possible to meet the drive requirements regarding starting (maximum) torque and maximum speed without the need for flux weakening technology.

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