Bojan ŠTUMBERGER, Miralem HADŽISELIMOVIĆ[1]

University of Maribor, Faculty of Electrical Engineering and Computer Science (1)

Power and cooling capability of synchronous generator with interior permanent magnets: Laboratory verification of machine characteristics

***Abstract**. The paper presents an experimental verification of power and cooling capability of totally enclosed non-ventilated (TENV) synchronous generator with interior permanent magnets, designed to work as a part of autonomous unit mounted to the driveline shaft of the internal combustion engine (ICE).*

***Streszczenie.** Artykuł przedstawia eksperymentalną weryfikację wydajności energetycznej i chłodzenia całkowicie pozbawionego wentylacji generatora synchronicznego z wewnętrznym magnesem trwałym, zaprojektowanym do pracy jako samodzielna jednostka zamontowana na wale napędowym silnika spalinowego.(**Wydajność mocy i chłodzenia generatora synchronicznego z wewnętrznym magnesem trwałym: weryfikacja laboratoryjna charakterystyki generatora**)*

Keywords: power capability, cooling capability, synchronous generator, permanent magnets, laboratory verification.
Słowa kluczowe: wydajność energetyczna, wydajność chłodzenia, generator synchroniczny, magnesy trwałe, weryfikacja laboratoryjna

Introduction

Three-phase permanent magnet synchronous generators can be in the last few years frequently found in different applications where high efficiency, great power and cooling capability is desired over a wide speed range. Typical representative applications for permanent magnet machines can be found in the automotive industry where permanent magnet machines are used as starters/alternators, torque boosters and in different wind turbine generator systems for electric energy production as well.

In the automotive applications, a synchronous machine with permanent magnets is often exposed to high ambient temperatures and not particularly good cooling conditions. Therefore permanent magnet synchronous machines have to be designed with great care, which sometimes represents a difficult task [1-5] .

The paper presents an experimental verification of power and cooling capability of totally enclosed non-ventilated (TENV) synchronous generator with interior permanent magnets, designed to work as a part of autonomous unit mounted to the driveline shaft of the internal combustion engine (ICE). The generator has to fulfill the following requirements:

- nominal continuous electric power 4.0 kW at nominal speed of 3000 rev/min;
- maximal working speed 5000 rpm;
- short-time overload capability, 2 times higher than the nominal power:
- low value of cogging torque;
- low value of 5th, 7th, 11th and 13th harmonic in the line-to-line voltage waveform in no-load and load conditions;
- normal ambient working temperature 50^0 Celsius;
- desired efficiency at nominal load higher than 92 %;
- used insulation class F.

The three-phase permanent magnet synchronous generator with interior permanent magnets has been designed in accordance with the above mentioned requirements. Special attention has been devoted to proper selection of stator-slot/rotor-pole number combination in order to avoid stator slot skewing, relatively simple rotor geometry and appropriate selection of permanent magnet material. After design process, the permanent magnet synchronous generator with interior permanent magnets has been manufactured and tested in the laboratory environment.

Method of analysis

The performance prediction of three-phase permanent magnet synchronous generator with interior permanent magnets is made by the time-stepping finite element analysis. The influence of iron losses on generator performances was considered in the analysis by the posterior iron loss calculation [6, 7]. Several stator-slot/rotor-pole combinations were taken into account.

In order to determine suitability of the best generator design, the maximal temperatures for different loads in different generator parts were calculated by using Motor-CAD software.

For the final generator design the generator with 36 slots/8 pole combination with double-layer distributed winding has been determined as the best generator design in order to fulfil design requirements (outer stator diameter 200 mm, inner stator diameter 125 mm, active core length 100 mm, iron core material non-oriented electrical steel M330-35A, permanent magnet material NdFeB with parallel magnetization, B_r=1.08 ~ 1.13 T, H_{cB}= 805 ~ 860 kA/m at 20^0 C and maximal allowed continuous working temperature 200^0 C, winding insulation class F).

Photo of manufactured TENV synchronous generator with interior permanent magnets is presented in Fig. 1.

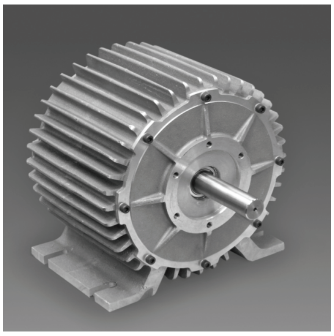

Fig. 1. Photo of TENV synchronous generator with interior permanent magnets

Results and discussion

The flux distribution in the cross-section of the generator for no-load and nominal load is presented in Fig. 2 and Fig. 3.

During the design process the following additional limitations were taken into account: maximal allowed peak to peak value of line-to-line voltage at no-load was limited to 300 V at maximal speed 5000 rpm and maximal allowed working temperature of permanent magnets at nominal load was limited to 140^0 Celsius. According to thermal calculations for the nominal load and speed the maximal obtained temperatures in permanent magnets were approximately for 15^0 C$-$$25^0$ C higher than average temperatures in generator windings and on generator housing. Real cooling capability, however, mainly depends on the maximal ambient temperature and temperature of the base on which the generator is fixed.

In order to determine real power and cooling capability of the manufactured generator the measurement set-up presented in Fig. 4 was used.

Permanent magnet synchronous generator was driven by the close-loop controlled induction motor and loaded by the resistive three-phase load.

Three-phase power transformer was used for voltage adjustment at the load side due to the measurements of generator characteristics for different loads over a wide speed range of operation.

Variation of measured line-to-line voltage, power factor, output power capability and efficiency in dependency on speed for different loads are presented in Fig. 5 − Fig. 10, while the temperature rise test results for nominal load and speed (3000 rpm) are presented in Fig. 11 − Fig. 16.

From the results presented in Figs. 5 and Fig. 6 it can be seen that terminal line-to-line voltage remains sinusoidal waveform even under load conditions. Due to the influence of power transformer reactances the power factor for low load levels and higher speeds is far from unity value, which can be seen in Fig. 9.

From the results of temperature rise test for nominal load and speed it can be seen that with the increasing of temperature, input power, output power and total losses are systematically decreasing till the thermal equilibrium is reached, while the efficiency remains practically constant.

This effect is mainly caused by the changing of working point of used permanent magnet material with the increasing of temperature.

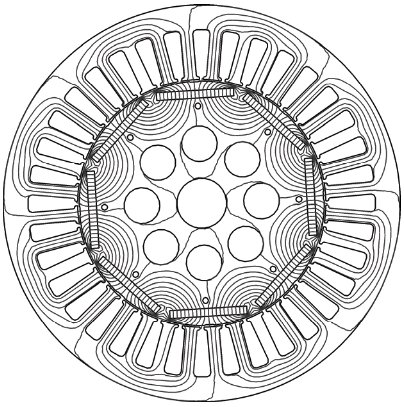

Fig. 2. Flux distribution in the cross-section of the generator when only PM excitation is applied

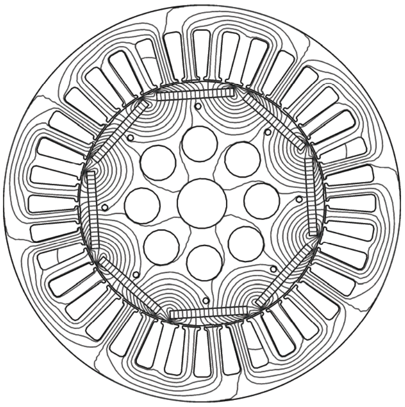

Fig. 3. Flux distribution in the cross-section of the generator when PM excitation and current excitation (phase current 25 A RMS, sinusoidal current waveform, q axis excitation) are applied simultaneously

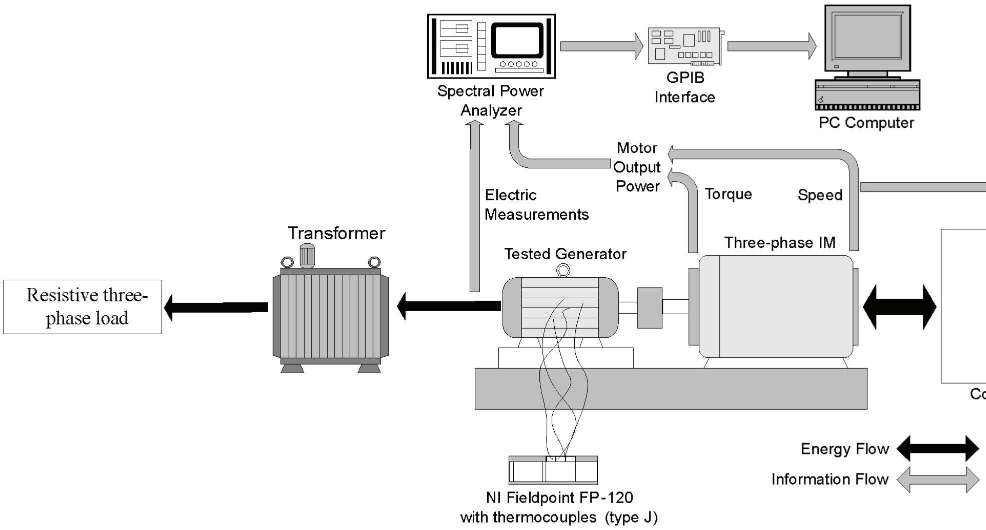

Fig. 4. Schematic presentation of measurement set-up

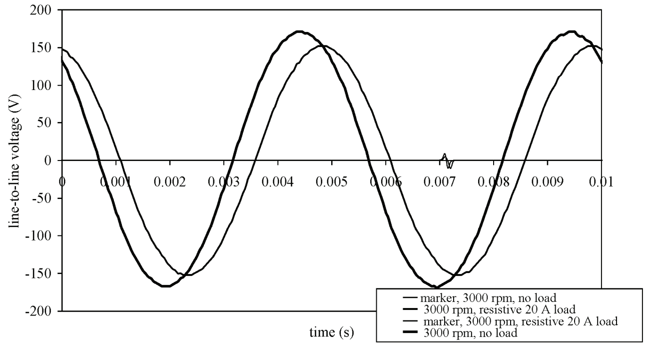

Fig. 5. Line-to-line voltage waveform at 3000 rpm at no-load and for the load case (resistive load, phase current 20 A RMS)

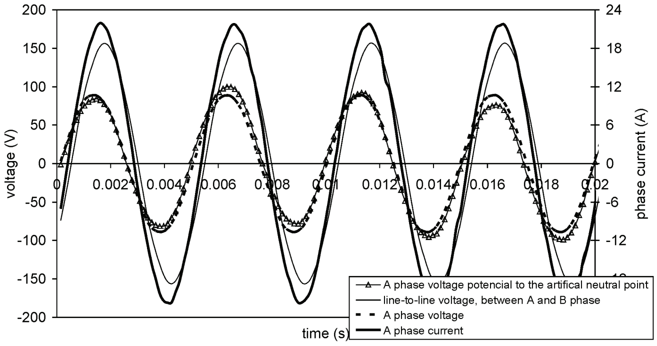

Fig. 6. Line-to-line voltage waveform, phase voltage waveform and phase current waveform at 3000 rpm for the load case (resistive load, phase current 20 A RMS)

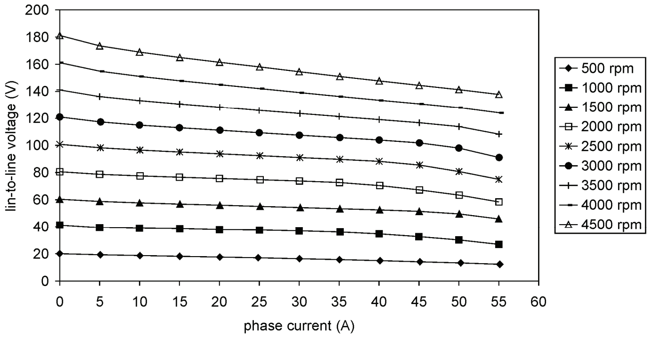

Fig. 7. Measured dependency of RMS value of line-to-line voltage in dependency on phase current for different speed levels

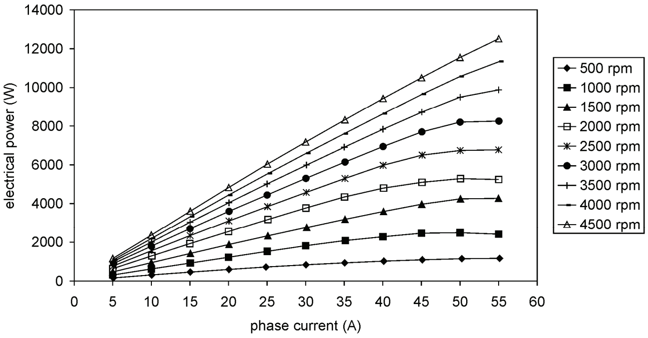

Fig. 8. Measured output power capability in dependency on phase current for different speed levels

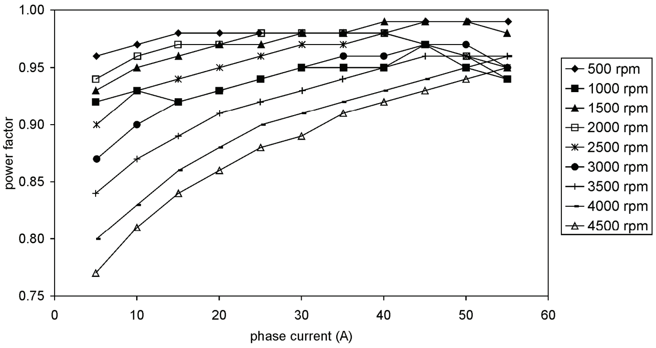

Fig. 9. Measured power factor value in dependency on phase current for different speed levels

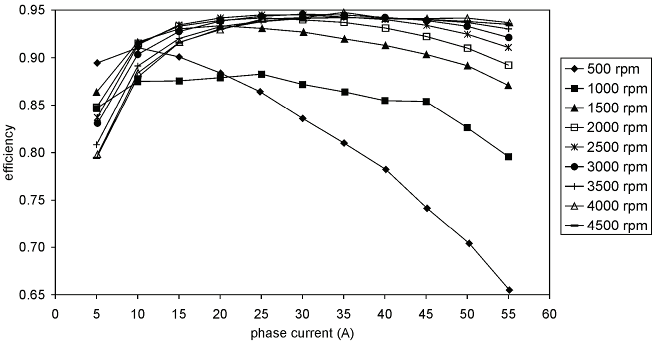

Fig. 10. Measured efficiency in dependency on phase current for different speed levels

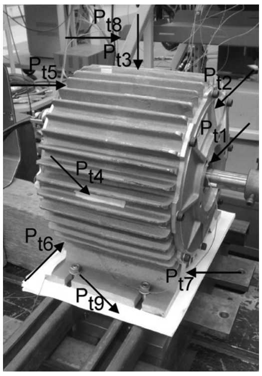

Fig. 11. Position of thermocouples placement during temperature rise test

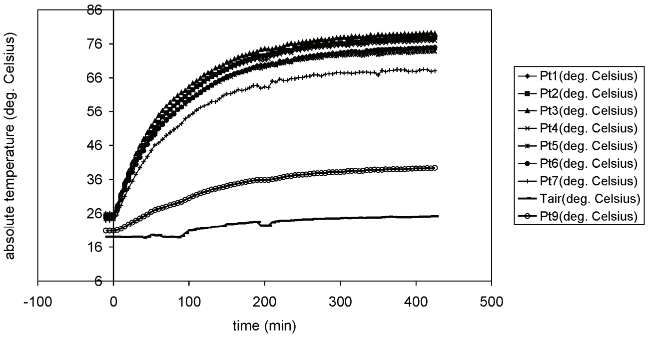

Fig. 12. Temperature rise test results for nominal load and speed

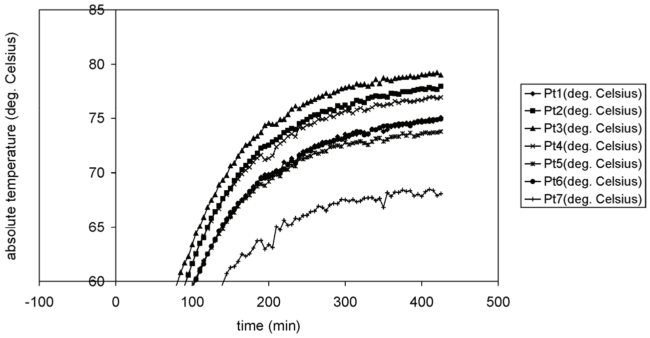

Fig. 13. Temperature rise test results for nominal load and speed (zoom from Fig. 12)

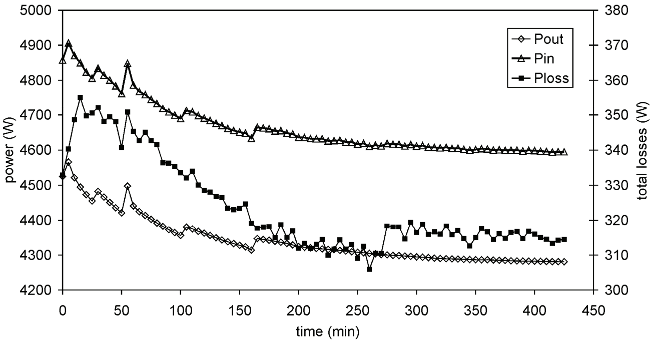

Fig. 14. Variation of output power, input power and total power losses during temperature rise test for nominal load and speed

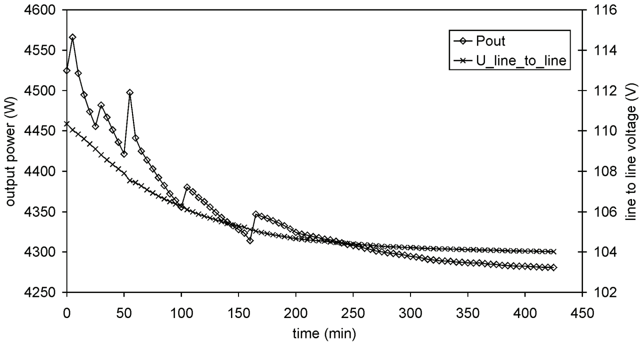

Fig. 15. Variation of output power and line-to-line voltage during temperature rise test for nominal load and speed

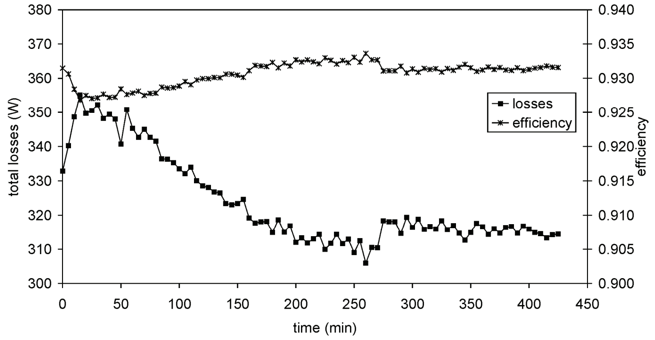

Fig. 16. Measured efficiency during temperature rise test for nominal load and speed

Conclusion

The results of laboratory verification presented in the paper clearly show that designed permanent magnet synchronous generator with interior permanent magnets fulfills all demands regarding desired power and cooling capability.

REFERENCES

[1] Štumberger B. et. al., Permanent magnet brushless DC motor; Integrated motor drive electricaly subsystem simulation, *Przegląd Elektrotechniczny*, 83 (2007), 135-138.

[2] Štumberger B. et. al., Modular permanent magnet synchronous motors for wheel-hub drive applications, *Przegląd Elektrotechniczny*, 84 (2008), 241-244.

[3] Štumberger B. et al., Evaluation of saturation and cross-magnetization effects in interior permanent-magnet synchronous motor, *IEEE Trans. Ind. Appl.*, 39 (2003), No. 5, 1264-1271.

[4] Štumberger B. et al., Comparison of torque capability of three-phase permanent magnet synchronous motors with different permanent magnet arrangement, *J. Magn. Magn. Mater.*, 316 (2007), e261-e264.

[5] Štumberger B. et al., Design and finite-element analysis of interior permanent magnet synchronous motor with flux barriers, *IEEE Transactions on Magnetics*, 44 (2008), 4389-4392.

[6] Štumberger B. et al., Accuracy of iron loss calculation in electrical machines by using different iron loss models, *J. Magn. Magn. Mater.*, 245-255 (2003), 269-271.

[7] Štumberger B. et al., Analysis of iron loss in interior permanent magnet synchronous motor over a wide-speed range of constant output power operation, *IEEE Transaction on Magnetics*, vol. 36, no. 41 (2000), 1846-1849.

Authors: *Bojan Štumberger, Miralem Hadžiselimović, University of Maribor, Faculty of Electrical Engineering and Computer Science, Smetanova ulica 17, 2000 Maribor, Slovenia,*
E-mail: bojan.stumberger@uni-mb.si.