Grant No.: 641073

Bio-HyPP

Deliverable No	Title	Submission Due Date	WP/Lead
D2.6	Optimized electrical drive	31.01.2018	WP 2 / TU/e

Short Summary

This document describes the deliverable D2.6 „Optimized electrical drive“ (demonstrator)

The high-speed generator was developed using analytical methods. After modifications of the initially proposed design, it has been manufactured, characterized in static tests and it is ready for further experimental evaluation at MTT test facilities.

Printed Date

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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1 Introduction

The aim of the Bio-Hypp project is the development of a full scale technology demonstrator of a hybrid power plant – a combination of solid oxide fuel cells and a micro gas turbine. As a part of WP2 "Component Development and Optimization" an optimized electrical drive has been developed. The electrical drive operation is closely related to the operation of other components of the micro gas turbine system, defining its operating conditions.

This report constitutes of Deliverable 2.6 "Optimized Electrical drive" for the Bio-Hypp project, and covers the development, manufacturing and testing of drive components. It is subdivided into four chapters.

Chapter 2 describes objectives and requirements for the electrical drive development within D2.6.

Chapter 3 describes the development of the components of the electrical drive. It also shows the final chosen high-speed generator topology, as well as photos of the final generator prototype.

Finally, Chapter 4 draws conclusions.

2 Objectives and requirements

As a part of work package 2 "Component Development and Optimization", more specifically task 2.2.4, an optimized electrical drive has been developed. The electrical drive (electromechanical subsystem) consists of two major components: the high-speed generator and the power electronics.

At the beginning of the project, the following objectives and requirements were agreed on between the partners involved in this task - TU/e Electromechanics and Power Electronics (EPE) group and MTT:

- The generator will be designed within the constraints of the power electronics hardware used by MTT at the beggining of the project; adaptations of the commutation strategy within the power electronics, which might lead to the improved drive efficiency and voltage range, are possible.
- To maintain the compatibility with the existing power electronics hardware and the control strategy, it is preferred, but not obligatory, that the high-speed generator remains of the same type, therefore permanent magnet (PM) based.
- While developing the high-speed generator, beside optimizing the design in terms of the generator performance, the compatibility with the rest of MTT system needs to be maintained, having in mind the flexibility while assembling the micro gas turbine system of which the high-speed generator is an integral part.
- Next to technical aspects, the generator design needs also to account for the minimization of manufacturing costs (for mass production).

Based on previously stated objectives and requirements, it was agreed that TU/e EPE will lead the work on the high-speed generator development, focusing on redesign of the stator. MTT will take lead in further modifications of the inverter commutation and modifications of the rotor size and, optionally, suggest additional stator adaptations necessary to support these modifications.

3 Electrical drive design and testing

The initial development and design of the high-speed generator started with the development of the analytical correlations between the main generator dimensions and power producing capabilities. Namely, for the considered application, a very high power density is required from the generator, since relatively high power (~3.7 kW) needs to be converted from mechanical to electric form at a very high rotational speed (~ 240.000 rpm), therefore with limited rotor volume. The preferred electric machine type for these requirements is a permanent magnet (PM) machine. PM machines have the highest power density in comparison to other machine types that could potentially be used at the required speed level (induction or switched reluctance machines). Furthermore, they have the highest efficiency, which is, besides the efficiency itself, important for keeping loss density (in the relatively small generator volume) at low level. Having this in mind this, as well as the experience that both TU/e and MTT have with high speed permanent magnet machines, it was decided that this machine type will be used for the high-speed generator.

To properly analyze and design high-speed PM machines, the influence of eddy-current effects on the machine performance needs to be included in the used models. Due to the fact that numerical (finite element) models which include eddy-current effects are very time consuming, analytical models are preferred. Therefore, analytical models were used for the generator design, with final validation performed by the finite element simulations. By using fast analytical models, the influence of eddy currents inside materials with different electromagnetic properties is evaluated very effectively, which is essential for the analysis of electromagnetic losses.

For the chosen machine type (PM machine), several different topologies of windings (stator coils) were analyzed [1], also considering the influence of power electronics on the machine performance. Based on the obtained results, it was concluded that for the considered application, concentrated winding layout, as well as distributed winding layout with lower number of slots, would both lead to high values of losses. More specifically, either rotor losses would be high (leading to magnet heating and potential demagnetization) or high number of turns in the stator coils would be required, leading to a high value of stator winding resistance.

Therefore, the generator development was directed towards a solution entailing a distributed winding with the number of slots higher than 6. As already stated in the previous chapter, besides considering losses and electromagnetic performance, the compatibility of the generator with the existing system and its flexibility towards the assembly of the whole system has to be accounted for also.

Next to the advantages which distributed windings with higher number of slots bring with respect to the generator performance, they have one significant drawback. Namely, electromagnetically inactive parts of coils (so called end windings) occupy lots of space. In the generator used by MTT at the beginning of the project, around 40 % of the total axial length of the generator is occupied by the end windings, which is very impractical due to ineffective use of space. Furthermore, this arrangement of end windings brings practical problems during the manufacturing process, since it makes use of certain types of wires impossible. Eventually, since the manufacturing process cannot be automated, it also leads to increased manufacturing costs. A potential reduction of the space occupied by end windings gives more flexibility in the design of other MGT system components and contributes to better rotor dynamics stability, since it gives a possibility of putting radial bearings closer to each other.

Based on the previous considerations, TU/e proposed a high-speed generator design shown in Figure 1. Red, green and blue fields represent coils belonging to different phases; cooling sleeve is shown in pink, while the stator ferromagnetic core is shown in grey.

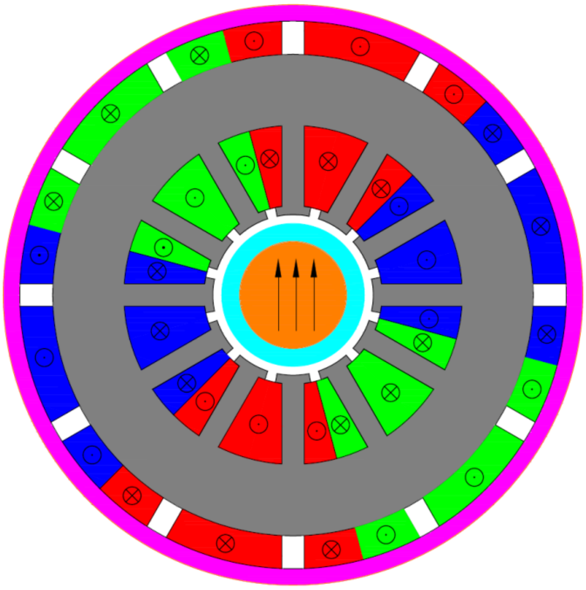

Figure 1: Originally proposed high-speed generator design

For the same length of the ferromagnetic core as with the previously used MTT generator (for the same generated power) the generator based on this design was expected to be shorter. The reason for this is the fact that end windings in this solution are not concentrated in the axial end regions of the generator, but on the outer side of the ferromagnetic core, between the stator core and the cooling sleeve. Since there were no strict limitations on the external diameter of the generator (the available space within the CHP system is more than sufficient), this solution was found to be very practical. The exact winding layout (the distribution of coils within stator slots) was chosen with the goal to keep eddy current losses in the rotor small, and it is similar to the winding layout in the generator used by MTT at the beginning of the project.

As previously mentioned, one of the criteria that has to be considered during the design of the high-speed generator is also the minimization of the manufacturing costs. After presenting the initial generator design, the manufacturer suggested several modifications which simplify the manufacturing process and make it fully automated, bringing the reduction in the production costs. The generator layout after adopting these modifications is shown in Figure 2. The layout of coils and their distribution within slots was modified (4 coils per phase were adopted instead of 6), although the total number of turns was kept the same. Furthermore, tooth tips were removed resulting in fully open slots. The original and the adopted design were evaluated against each other in terms of the electromagnetic performance and it was concluded that modifications will not significantly deteriorate the generator performance. Therefore, the adopted generator design was chosen for further development.

As a next step, several prototypes of the modified generator design received from the manufacturer were tested in static conditions at TU/e EPE lab. These involved a series of tests on few stators with different internal electrical connections of coils within the same phase, as well as with different cooling sleeve materials. The goal of these tests was to choose the prototype with the optimal design (lowest electromagnetic losses), which is still in line with the possibilities of the manufacturer regarding the cost effective mass production.

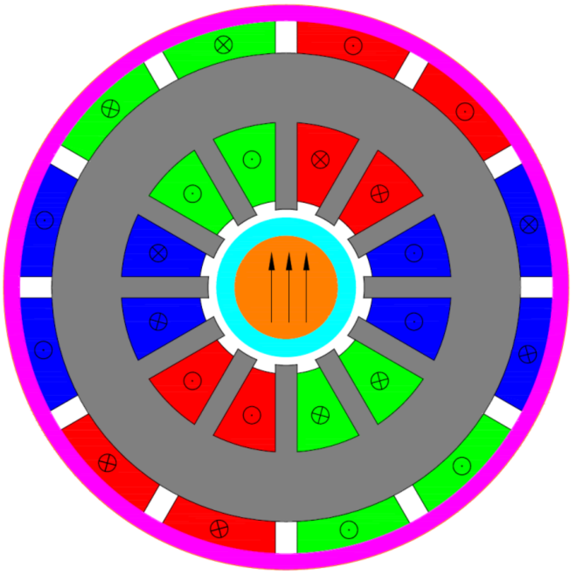

Figure 2: Adopted design of the high-speed generator

In parallel, a new stator cooling sleeve and housing have been designed and manufactured to accommodate the developed stator with greater external diameter. The housing for the new generator is shown in Figure 3.

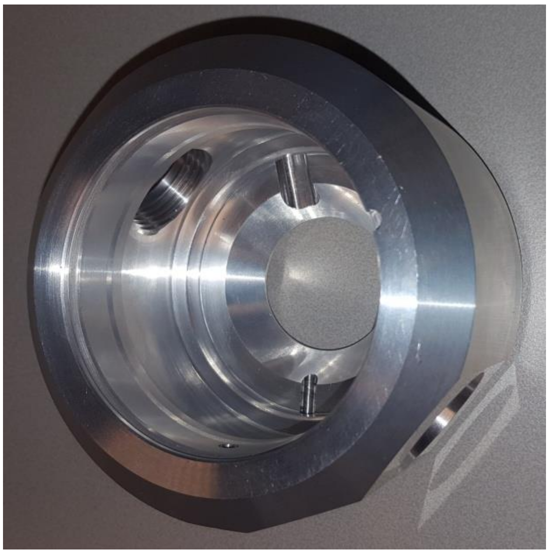

Figure 3: Housing for the new generator

In Figure 4, a generator prototype made according to the adopted design is shown during the manufacturing process, with clearly visible coils mounted around the stator ferromagnetic core. Furthermore, in Figure 5 the assembled stator with the cooling sleeve is shown. It should be noted that the cooling sleeve shown in Figure 5 is made of aluminium based alloy, and represents one of the prototypes made during the development process. The finally chosen sleeve is made of copper, which gives lower eddy-current losses in the sleeve itself. This sleeve is shown in Figure 6. The total axial length of the stator shown in Figure 5 is 42.5 mm, which is reduced in comparison to 49 mm axial length of the stator used by MTT at the beginning of the project.

Figure 4: The stator of the high-speed generator during the manufacturing process

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Figure 5: Assembled stator of the high-speed generator, with aluminium based cooling sleeve

Figure 6: Copper sleeve of the high-speed generator, used in the final prototype

Based on the feedback from the series of tests performed at TU/e EPE lab, the stator based on the optimal design with the copper sleeve was manufactured and is currently being prepared for further dynamic tests at MTT test facilities and integration with the micro gas turbine. The complete stator with copper sleeve and electrical connections is shown in Figure 7 and Figure 8.

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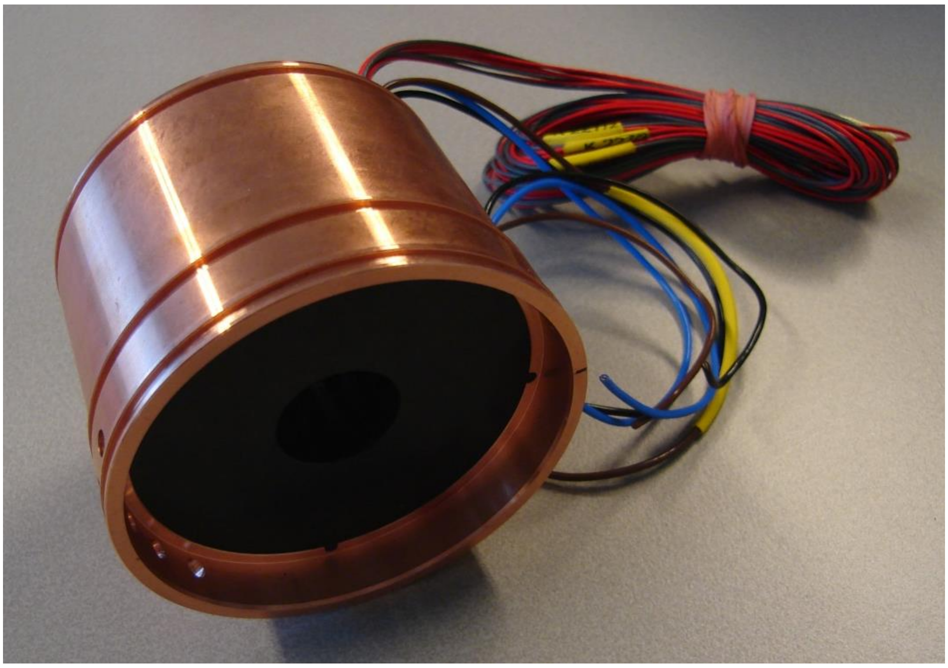

Figure 7: Manufactured stator with copper sleeve

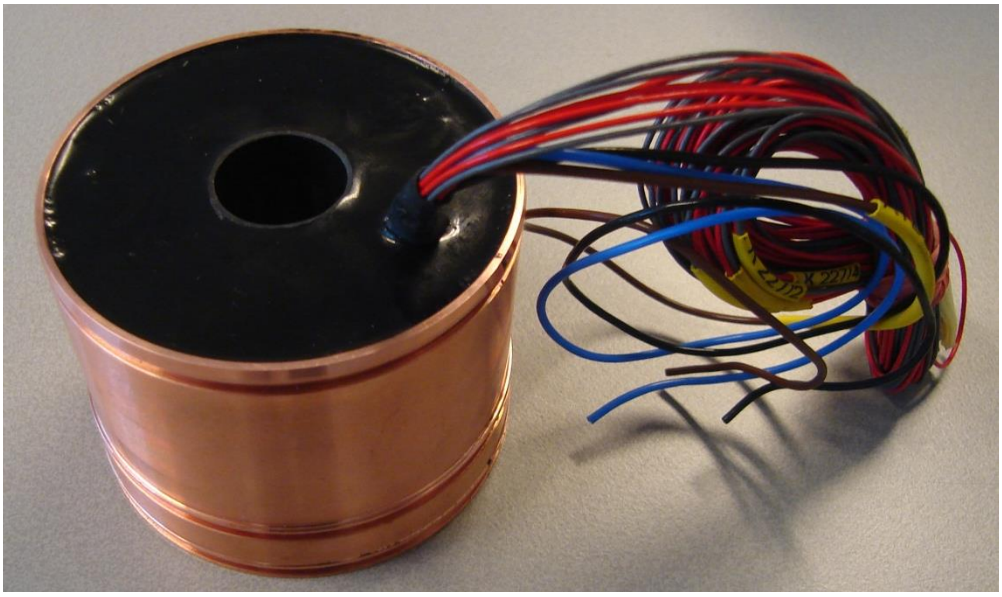

Figure 8: Manufactured stator with copper sleeve

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4 Conclusion

A high-speed permanent magnet generator has been designed using analytical methods. This enables fast design process and easy assessment of the influence of variations in material properties. The initial design was adopted according to the manufacturer's feedback. A series of static tests on several prototypes have been performed and the optimal stator design was chosen for the final prototype. This prototype has been manufactured and will be subjected to further experimental investigation in dynamic tests at MTT test facilities.

References

[1] M. Merdzan, J. J. H. Paulides and E. A. Lomonova, "Comparative analysis of rotor losses in high-speed permanent magnet machines with different winding configurations considering the influence of the inverter PWM," *2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte Carlo, 2015, pp. 1-8. doi: 10.1109/EVER.2015.7112942