Experimental Tests on a 9-phase Direct-Drive PM Axial-Flux Synchronous Generator

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***Abstract*—A small power 9-phase axial-flux PM synchronous generator was built to validate the design and optimization process of a 5MW direct-drive wind turbine. Two quality criteria are imposed for the system. The electromagnetic torque of the generator and the DC bus current of the rectifier must not contain low-order harmonics. Nominal load tests, where the generator is supplied via 9-phase IGBT rectifier and the control is realized using the multi-machine multi-converter systems concept, allow verifying these criteria. The parameters of the machine are determined using no-load tests. The results obtained by numerical and analytical models are compared with the experimental measurements.**

***Index Terms*—Axial-flux, PM synchronous generator, polyphased machine, experiments.**

I. Introduction

THE wind generators, the so-called direct-drive wind turbines, characterized by high torque and low speed parameters, represent one of the PM synchronous machines applications in the energy industry. The nowadays applications, using PM generators, have nominal power up to 5 MW for geared drive solutions. For the gearless drives, up to 3MW systems are reported for on-shore applications [1].

A PM machine was designed for a direct-drive 5 MW wind generator application. The machine is an axial-flux one, using a polyphased concentrated winding. Polyphased structures offer the advantage of modularity, with immediate consequences for the fabrication process, assembly, transportation and maintenance.

Several solutions can be considered: sinusoidal or trapezoidal waveform [2], 3-phase and polyphased systems. Different systems, with different number of phases and different shift displacement were compared in [3].

Numerical models were used for preliminary studies for both machine and converter. To investigate the performances of polyphased systems, a real time vector control is implemented. The configuration chosen based on the system specification and imposed quality criteria, consists in 9-phase system, where each star is supplied via a 3-phase back-to-back converter, and the converters are parallel connected via the DC bus.

The first quality criteria is the electromagnetic torque, and the interest is to minimize torque oscillations, which cause lower mechanical stability, audible noise and accelerated ageing of the machine due to vibrations.

The DC bus current represents the second quality criterion. To avoid over-voltage and to protect the transistors, the control of the inverter imposes a constant DC voltage. If the DC voltage is maintained constant, the DC current waveform will give an indication about the power transfer. Reducing harmonic content of the DC bus current will allow reducing the size of the DC bus filter and the harmonic filter at the output of the converter.

To validate the analytical and numerical models, a small-scale prototype was built. The paper describes the fabrication technique and the different tests realized to verify the quality criteria. In terms of modeling, the multi-machine multi-converter systems (MMS) concept is used to realize the control of the system in order to maximize the regenerated power.

II. The Prototype

The generator is a polyphased one, where the 9 phases form a triple-star configuration where the windings are uniformly distributed. Its architecture consists on a discoid, axial flux, two outer stators and one interior PM rotor (Fig. 1a and 1b), where the magnets, placed face-to-face on both sides of the rotor, have opposite polarities (North South – NS – topology).

Each stator has 9 slots. The stators are realized from one long rolled metal sheet (fig. 1b), and the slots are cut-off with a constant width. The winding is a concentrated one (fig. 1d), which avoids coils overlapping. It represents a very promising solution because the coils are very easy to insert in the slots. The end-windings are shortened compared to a distributed winding. Therefore, the radial bulk and the copper losses are reduced.

The prototype has 10 poles. The magnets have trapezoidal shape (fig. 1e) and the magnet pole arc to pole pitch ratio is 0.8.

The construction allows variation of the air-gap thickness and variation of the mechanical angle between the two stators, which allows investigating their influence on parameters of

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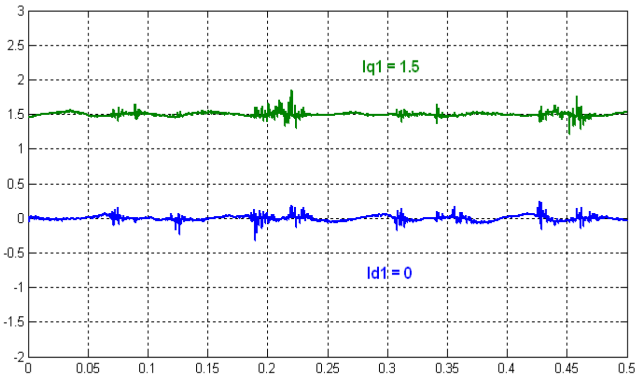

Fig. 11 - d, q currents of the main machine

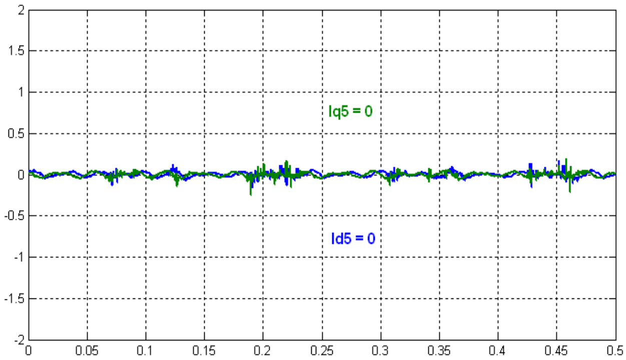

Fig. 12 - d,q currents of the second fictitious machine

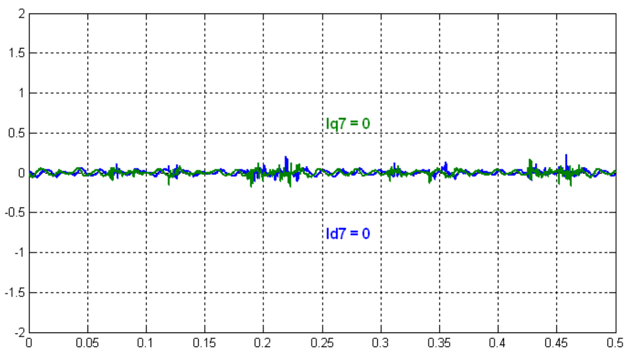

Fig. 13 - d,q currents of the fourth fictitious machine

VI. Conclusion

A small scale 9-phase axial flux PM generator was built to validate the design and optimization processes of a 5MW wind turbine. A comparison is done between the results obtained from numerical and analytical models on one hand, and experimental measurements on the other hand. A good correlation was found for the phase no-load EMF, phase resistance, mutual inductances, cogging torque and DC bus current. However, significant differences occur for the cyclic inductance and the power factor. The analytical conception does not take into consideration the saturation effect, end-windings inductance, which seems to be important for machines with short stator yoke length.

The dynamical performances are evaluated using MMS concept, which allows the transformation of a polyphased

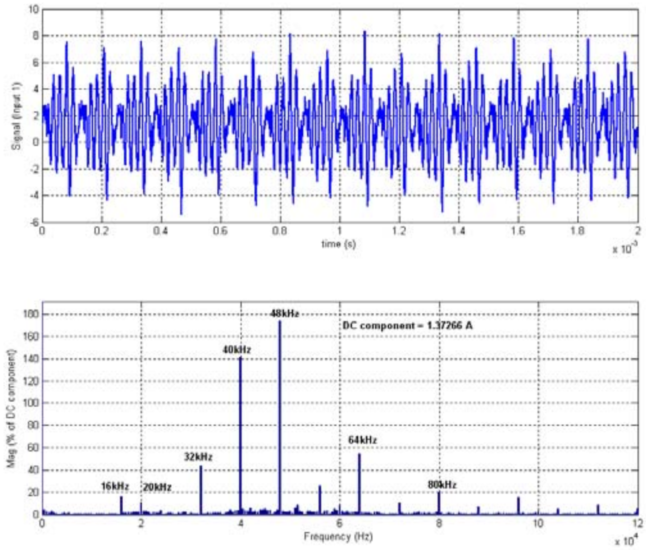

Fig. 14 – DC bus current and its FFT analysis

machine into several fictitious one-phase or two-phase machines, leading to an easier analysis and control. The experimental results validate the MMS method for a 9-phase PM axial flux synchronous generator and confirms the results obtained for the quality criteria by numerical simulations.

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