Electromagnetic Design and Finite-Element Analysis of an Axial-Flux Permanent-Magnet Machine

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***Abstract*— This paper approaches the electromagnetic design and finite-element analysis of an axial-flux permanent-magnet (AFPM) synchronous generator for small-scale wind turbines. The study is conducted to find a good-performance and cost-effective electric generator topology for micro-wind power application. The proposed double-sided two-stators-one-rotor AFPM synchronous generator with non-overlapping concentrated slotless-stator-winding and ironless PM-rotor disk could be the machine of choice in grid-connected or stand-alone small-scale wind energy conversion systems.**

Keywords—axial flux; permanent magnet; wind energy;

I. INTRODUCTION

Despite their great potentials small-scale wind turbines reveal low penetration in the renewable-energy production market, as compared with large utility-size wind turbines, due to the following main reasons [1]: (i) micro-wind turbines operate mostly in low-wind-speed areas, experiencing self-starting problems, which have negative consequences on the energy yield; (ii) the cost per installed kW of current stand-alone micro-wind turbines is much higher than that for large wind turbines; (iii) micro-wind turbines require good technical skills and rather complex equipment in manufacturing and maintenance processes, which increase their installing and operational costs.

Many micro-wind turbine manufacturers use direct-driven generators [2], thus avoiding mechanical gear, reducing size of the entire system, lessening noises and lowering installation and maintenance costs. However, a direct-driven micro-wind generator has to operate at very low speeds in order to match the wind turbine speed, and to produce electricity within a reasonable frequency range; hence, the micro-wind generator has a rather big size, and must be designed with a large number of poles.

Axial-flux permanent-magnet (AFPM) synchronous generators are increasingly being used in the last decade for direct-drive small-scale wind turbine applications [3, 4]. Compared with conventional radial-flux PM machines, the AFPM synchronous generators have the advantages of more compact structure due to the flat shape with short axial-length, larger power-to-weight ratio and torque density, more flexible PM-field and armature-winding design, better cooling and modular construction. The drawback of a low-speed direct-driven AFPM synchronous generator is that it requires larger diameter, which affects the material cost of the machine [5].

The double-sided two-stators-one-rotor AFPM synchronous generator topology with non-overlapping concentrated slotless-stator-winding and ironless PM-rotor disk is considered in this paper, which is organized as follows. In Section II, the preliminary electromagnetic design of the proposed double-sided internal-rotor AFPM synchronous machine for use as a direct-driven generator with small-scale wind turbines is addressed. Section III presents the 3-D finite-element field analysis and simulation results for the double-sided AFPM synchronous generator design evaluation. Conclusion is drawn in Section IV.

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II. PRELIMINARY ELECTROMAGNETIC DESIGN OF THE AFPM SYNCHRONOUS GENERATOR FOR SMALL-SCALE WIND TURBINES

The considered AFPM synchronous generator has an inner PM-rotor with eight pole-pairs of axially-magnetized NdFeB-type magnets, which are accommodated in an ironless disk. External slotted stators may increase notably the airgap flux density due to the reduced clearance between rotor and stator. The required amount of rotor-PMs becomes smaller, thus lowering the global cost of the machine. On the other hand, the use of slotted-stator armature winding results in significant cogging torque and content of harmonics in the back-emf waveform. Such problems must be tackled efficiently from the electromagnetic design viewpoint.

References [6, 7] advocate the application of slotless-stator concentrated non-overlapping armature-winding in AFPM synchronous generators, since the winding process using prefabricated coils is cost-effective. Furthermore, the space needed by the end-windings and thus the copper losses are minimized.

The rated power of the AFPM synchronous generator under study is of 2.5 kW for the rotational speed of 200 rpm.

By applying the general sizing equation to the small AFPM synchronous generator under study, the outer surface diameter D_o is obtained as

$$D_0 = \left[\frac{8}{\pi^2} \frac{p}{f} \frac{P_{out}}{k_i k_p \eta (1+\lambda)(1-\lambda^2)(B_g)} \right]^{1/3} . \quad (1)$$

The total outer diameter of the machine is given by

$$D_{tot} = D_0 + 2W_{Cu} , \quad (2)$$

and the total axial length of the machine can be expressed as

$$L_{tot} = L_r + 2L_S + 2g \quad (3)$$

where the rotor axial length sums the rotor-core and rotor-PM contributions, i.e.

$$L_r = L_{r,core} + 2L_{PM} = B\frac{B_u}{B_{r,core}} \cdot \frac{\pi}{8} \frac{(1+\lambda)D_0}{p} + \frac{\mu_{r,PM} B_g}{B_{rem} - \frac{k_f}{k_d} B_g} g \quad (4)$$

with $B_{r,core}$ representing the flux density in the rotor-disk core; B_u, the attainable flux density on the surface of the rotor-PM; $\mu_{r,PM}$ and B_{rem}, the relative permeability and the remanent flux density of the rotor-PM material, respectively; k_d and k_f, the leakage flux factor and the peak-value-corrected radial-airgap flux-density factor of the machine, respectively; k_e , the back-emf factor, i.e. the armature-winding distribution factor; N_{ph}, the number of turns in series per armature-winding phase; f , the mains electrical frequency; p, the number of machine pole-pairs; D_i , D_o, the diameters of the inner and outer surfaces of the machine, respectively; $\lambda = D_i / D_o$, the inner-to-outer diameter ratio; $\hat{B}_g$, the peak value of the magnetic flux density in the airgap (magnetic loading); g, the airgap axial length.

The stator axial length sums the stator-core axial length

$$L_S = L_{s,core} \quad (5)$$

where

$$L_{s,core} = \frac{B_g}{B_{s,core}} \cdot \frac{\pi}{4} \frac{\alpha_p (1+\lambda) D_0}{p} \quad (6)$$

with $B_{s,core}$, the flux density in the stator core; α_p, the ratio of the average airgap flux density to the peak value of the airgap flux density; J_{slot}, the stator-slot current density; k_{Cu}, the copper-fill factor.

The analytical preliminary electromagnetic design has been used for determining the main data of rotor and stator components for the small three-phase AFPM synchronous generator, listed in Table I.

Table I Main design data of the small three-phase double-sided inner-rotor AFPM synchronous wind-generator

Design data	Value
Turns per stator-winding phase	2500
Turns per coil	312
Wire diameter [mm^2]	0.5
Slot-fill factor (gross)	0.5
Stator phase-winding resistance [Ω]	12
Rotor-PM thickenss [mm]	20
Airgap clearance [mm]	2
Number of PM-rotor poles	16
Outer radius [mm]	295
Rated rotational speed [rpm]	200
Rated output power [W]	2500

III. 3-D FINITE-ELEMENT FIELD ANALYSIS OF THE AFPM SYNCHRONOUS GENERATOR FOR SMALL-SCALE WIND TURBINES

Due to rapid advances in computational methods, a number of 3-D finite-element (FE) field analysis software packages are now available, so that a given field problem may be solved by a judicious choice of the software tool. In this paper, the design evaluation of the small three-phase double-sided inner-rotor AFPM synchronous wind-generator is conducted by time-stepped 3-D FE field analysis using the commercial software JMAG-Studio.

The time-stepping FE field-circuit solution procedure entails the following steps:(i) build the geometric field model and the coupled circuit model of the AFPM wind-generator; (ii) build the sliding surface for time-stepping analysis; (iii) select solver, boundary conditions and time increment; (iv) execute the program to obtain the FE field-circuit solution.

Rotor-PM flux-density distribution from 3-D FE analysis of the small double-sided inner-rotor AFPM synchronous wind-generator is presented in Fig. 1, which proves that magnetic saturation in the PM-rotor disks is not of concern.

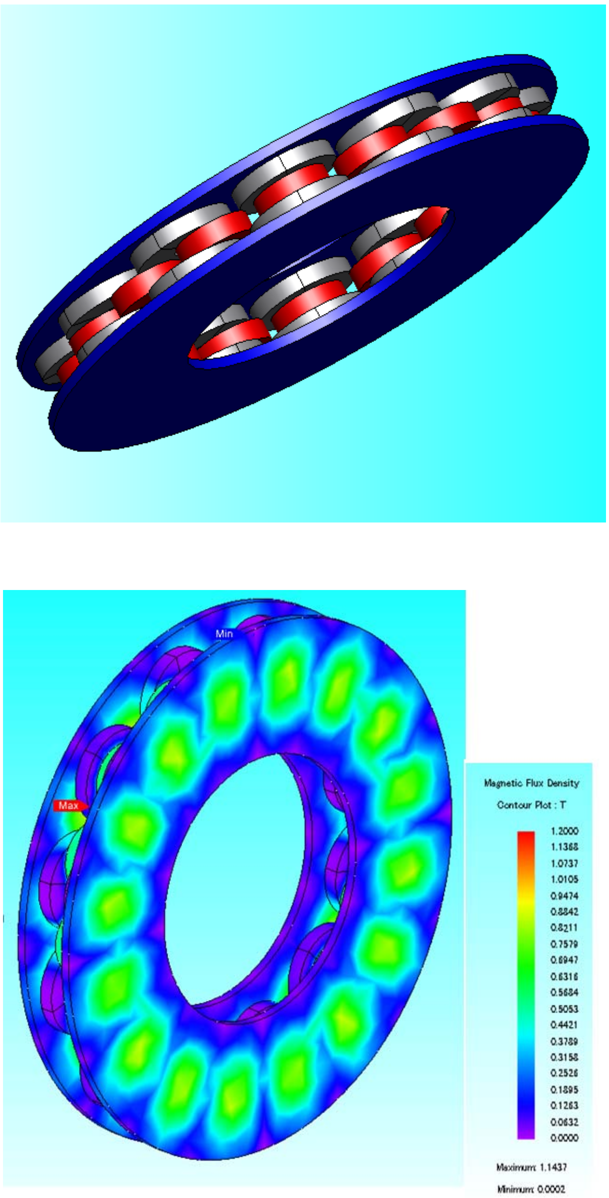


Fig. 1. Rotor-PM flux density distribution in the small double-sided inner-rotor AFPM synchronous wind-generator.

The induced back-emf waveforms under no-load (open stator-circuit) condition are computed in Fig.2, showing a rms-value of about 364 [V/phase].

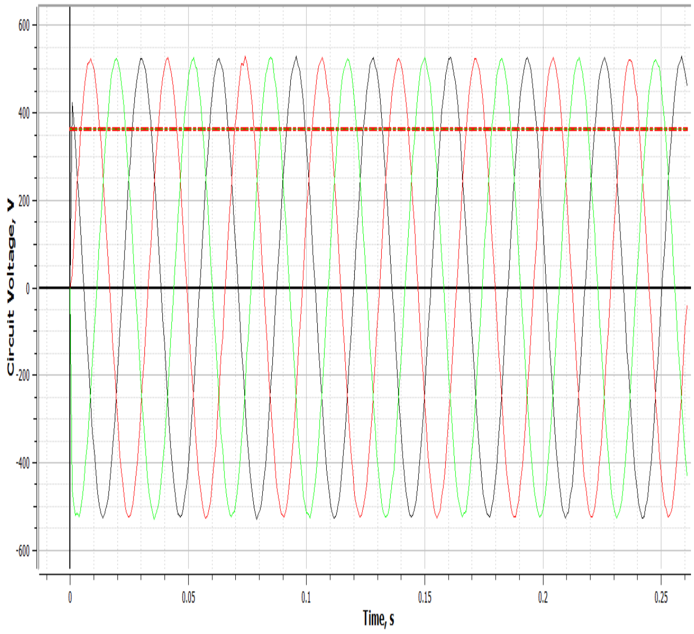


Fig. 2. FE-computed line back-emfs of the small double-sided inner-rotor AFPM synchronous wind-generator under no-load condition

The performance of the small double-sided inner-rotor AFPM synchronous wind-generator supplying an isolated, three-phase resistive load of 158 [Ω/phase] is computed using the 3-D FE time-stepping analysis. Fig. 3 presents the FE-computed dynamic electromagnetic torque. It can be seen that the mutual torque ripple caused by harmonic components of the developed electromagnetic torque is quite significant.

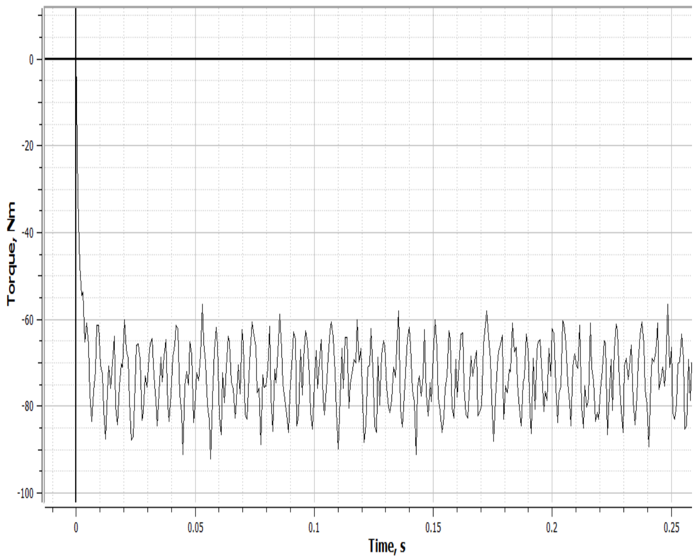
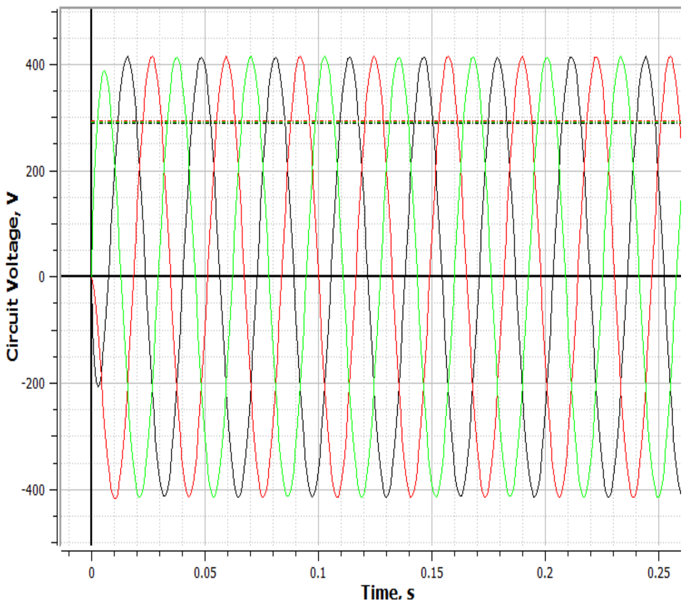


Fig. 3. FE-computed dynamic electromagnetic torque of the small double-sided inner-rotor AFPM synchronous wind-generator under resistive load condition.

Fig. 4 shows the FE-computed stator-winding line-voltage and line-current waveforms, which are practically sinusoidal. It is to be noted, that the computed waveforms have taken into account the geometry of the stator-armature winding coils.



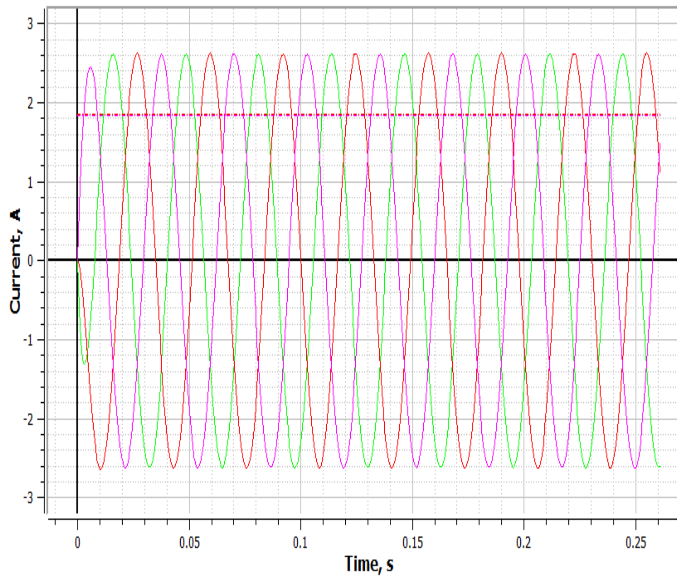


Fig. 4. FE-computed stator-winding line-voltage and line-current waveforms for the small double-sided inner-rotor AFPM synchronous wind-generator under resistive load condition.

The FE-computed results, as well as the active material masses from the design analysis of the small double-sided inner-rotor AFPM synchronous wind-generator are summarized in Table II.

Table II Design FE-analysis results for the small double-sided inner-rotor AFPM synchronous wind-generator

Design FE-analysis result	Value
Copper mass of the stator winding [kg]	25
Mass of rotor PMs [kg]	9.93
Iron mass of stators [kg]	25
Total mass [kg]	60
I_{rms} [A]	1.85
U_{rms} [V]	298
Stator-winding copper losses [W]	130
Torque [Nm]	75
Active materials estimated cost [Euro]	350
Manufacturing cost factor	1.5
Total estimated cost [Euro]	525

IV. CONCLUSIONS

Electromagnetic design of a small double-sided inner-rotor AFPM synchronous wind-generator has been addressed and discussed in this paper. Its two-stators-one-rotor topology with non-overlapping concentrated slotless-stator-winding and ironless PM-rotor disk makes this design well suited for low-speed micro-wind generator applications. The FE-based design analysis results have shown its good performances in output characteristics, electromagnetic torque and overall cost effectiveness.

V. ACKNOWLEDGEMENT

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