Design Analysis of a Novel Double-Sided Axial-Flux Permanent-Magnet Generator for Micro-Wind Power Applications

Mihai CHIRCA, Stefan BREBAN, Claudiu OPREA, Mircea M. RADULESCU
Technical University of Cluj-Napoca, Cluj-Napoca, Romania
E-mails: Mihai.Chirca@mae.utcluj.ro, Stefan.Breban@emd.utcluj.ro, Claudiu.Oprea@emd.utcluj.ro, Mircea.Radulescu@emd.utcluj.ro

Abstract – This paper proposes an innovative topology for double-sided inner-stator axial-flux permanent-magnet (AFPM) machine for use as direct-driven generator with low-speed micro-wind turbines. The design evaluation of the new AFPM wind generator, based on 3-D finite-element field analysis, proves that the ironless stator with non-overlapping concentrated winding, sandwiched between two opposing steel-rotor disks with embedded circumferentially-magnetized PMs in flux-concentration arrangement, represents a good-performance and cost-effective double-sided structure for the AFPM machine of choice in micro-wind power generation applications.

I. INTRODUCTION

Despite their great potentials, micro-wind turbines of less than 10 kW rated capacity 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.

By adopting innovative design configurations for the micro-wind generator, the overall cost of micro-wind turbine systems can be significantly lowered. Moreover, the fabrication and maintenance processes may be simplified, and the complexity of the required equipment may be reduced.

Many micro-wind-turbine manufacturers use direct-driven wind generators [2], thus eliminating 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 (25–70 Hz); hence, the micro-wind generator has a rather big size, and must be designed with a large number of magnetic poles.

Axial-flux permanent-magnet (AFPM) generators are increasingly being used in the last decade for direct-drive micro-wind turbine applications [3, 4]. Compared with conventional radial-flux PM machines, the AFPM 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. Moreover, the disk shape of AFPM generator creates the ideal mounting plane for the wind-turbine blades. The drawback of a low-speed direct-driven AFPM wind-generator is that it requires larger diameter, which affects the material cost of the machine [5].

The double-sided AFPM machine topology with inner coreless (ironless) stator and two twin outer PM-rotors is considered as the topology of choice for low-speed micro-wind generator applications by the following reasons [6, 7].

It has the greatest torque production capability due to the increased volume of PM material used. As the magnetic losses in rotor PMs and disks are very small, and can be neglected as there is no change in the flux direction in the rotor back-iron, the rotor disks can be manufactured from solid iron. The outer-rotor configuration makes integration of generator to turbine simpler as generator can be bolted easily to turbine rotor.

Since the direct-driven AFPM generator operates at low speeds, on the one hand, the resulting centrifugal force on the rotor-PMs is relatively low, while, on the other hand, high rotor-pole number is required with the inherent penalty of excessive leakage flux between neighboring PMs, caused by the small pole-pitch. Besides, the PM-rotor disks account for roughly a half of the total mass of the AFPM generator; hence, the optimal rotor design is paramount in achieving high power-to-weight ratio.

The disadvantage of the double-rotor AFPM topology is the strong magnetic attractive force between the two opposing PM-rotor disks, which can cause the deflection of the rotor disks with the consequence of closing the running clearance between stator and rotor, as well as deteriorating the cooling capacity.

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The coreless (ironless and slotless) inner-stator configuration (i) has no iron losses; (ii) eliminates cogging torque, which makes it easier for the wind turbine to start at very low wind speeds; (iii) is facile to manufacture by avoiding the need for complex equipment required to make laminated stator core; (iv) has no attractive magnetic forces on each side to the outer rotor disks, provided that the stator winding is located precisely on the centre plane between the two rotor disks. Owing to a large airgap, the stator-armature magnetic reaction and the harmonics caused by the stator-winding m.m.f. space distribution are negligible. However, the absence of iron core for the coils of the stator windings (i.e. airgap windings) creates a low flux density in the magnetic circuit of the winding-coil, with the outcome of a low value of winding-phase inductance. Besides, there are induced eddy-currents in the stator-winding conductors, since they are exposed to alternating magnetic fields, in both axial and tangential directions, produced by the moving rotor-PMs.

This paper is organized as follows. In Section II, an innovative design of a double-sided inner-stator AFPM machine for use as a direct-driven generator with low-speed micro-wind turbines is proposed and argued. Section III presents the 3-D finite-element field analysis and simulation results for the new AFPM wind-generator design evaluation. Conclusion is drawn in Section IV.

II. DESIGN OF THE NOVEL DOUBLE-SIDED AFPM MICRO-WIND GENERATOR

The innovative design of a double-sided inner-stator AFPM wind-generator, for which a request for grant of a European patent was addressed, starts from some premises: (i) the micro-wind power system should be implemented primarily in urban areas, thus it should be very efficient in converting energy at low wind speeds; (ii) the wind generator is directly driven by the turbine and the associated electronic power converters should be controlled in a maximum-power-point-tracking strategy for connection to power grid, and should also satisfy the voltage constraints for connection to isolated loads [8].

The proposed topology of the double-sided inner-coreless-stator AFPM wind-generator is shown in Fig.1.

It provides a new outer PM-rotor disk structure with embedded rectangular-shaped PMs, having alternating circumferential magnetization (Fig.2) and interspersed iron pieces, constituting the rotor magnetic poles. This flux-concentration arrangement offers the following benefits:

- the flux density in the magnetic poles is higher than in the PMs, thus low-cost ferrite PMs can be used;
- the axial length of the machine may be extend to increase the magnetic flux linkage of the machine;
- if rare-earth PMs are to be used, the machine could be built in more compact size and with lower mass;
- the effective airgap is reduced due to embedded (not surface-mounted) rotor-PMs.

This new AFPM wind-generator design removes the constraint of the airgap magnetic flux mainly imposed by the rotor-PMs by proposing an innovative arrangement of PMs on the rotor that enables higher airgap magnetic flux, even if low-remanence PMs are used.

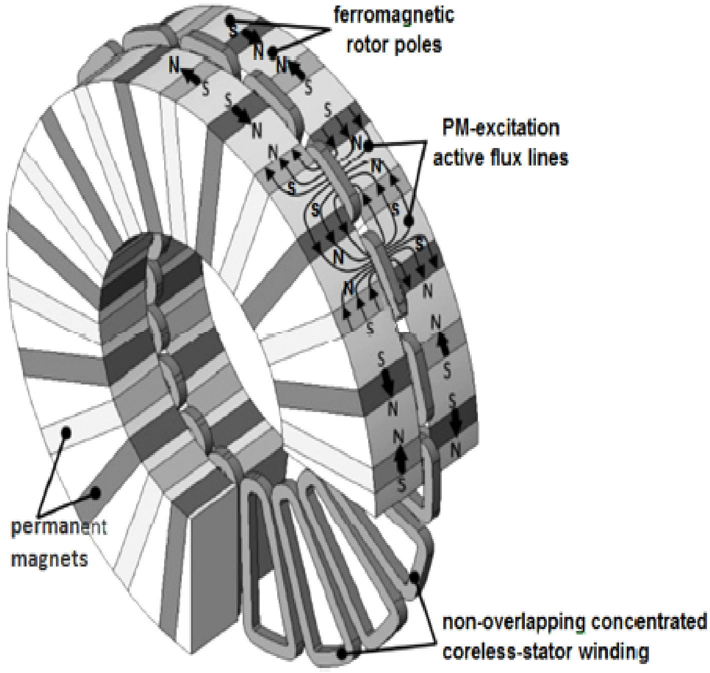


Fig. 1. Design features of the novel double-sided inner-coreless-stator AFPM wind generator.

The three-phase stator winding considered for the new double-sided internal-coreless-stator AFPM wind-generator is of non-overlapping concentrated winding topology, where the coils lie entirely next to each other in the same plane (Fig.1). The benefits of this coreless (airgap) winding layout are the reduced overall axial length of the machine, the shorter end-turn length, the lower stator-winding copper losses due to shorter average length of turns. Preformed trapezoidal-shape coils are packed in sequence, connected accordingly, and placed in the required position inside the non-magnetic and non-conductive stator-mould.

The coreless stator with slotless winding is cast with composite material of epoxy resin and hardener to build the disk-shape structure. The use of parallel thin round-wires in the winding-coil is preferred due to its reduced cost and availability, but with the penalty of a rather low coil-filling factor. By axial twisting of wires, the eddy-current loss component of stator-winding copper losses becomes negligible.

The main design data of the new double-sided internal-coreless-stator AFPM wind-generator are given in Table I.

TABLE I
MAIN DESIGN DATA OF THE NEW DOUBLE-SIDED INNER-CORELESS-STATOR AFPM MICRO-WIND GENERATOR

Design data	Value
Number of poles	24
Number of coils	18
Inner diameter [mm]	170
Outer diameter [mm]	370
Stator thickness [mm]	10
Rotor-disk thickness [mm]	50
Axial length [mm]	112
Airgap mechanical clearance [mm]	2
PM remanence [T]	0.4
Number of stator-winding phases	3

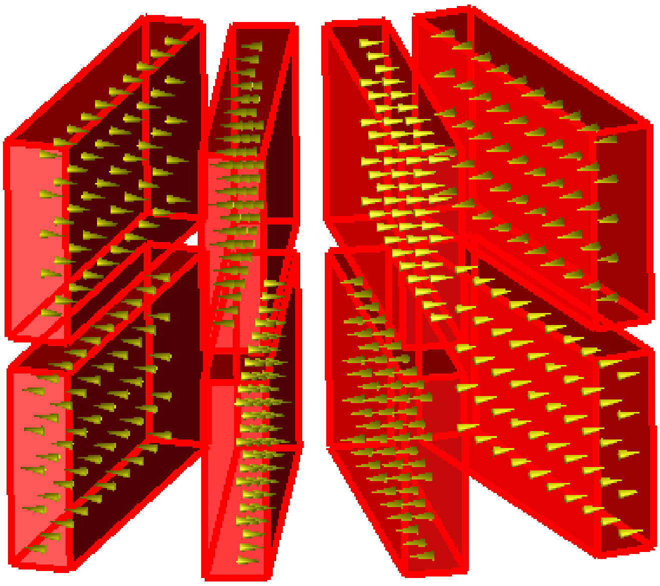


Fig. 2. Flux-concentration arrangement of embedded circumferentially-magnetized PMs on the two outer-rotor disks of the new double-sided AFPM wind-generator.

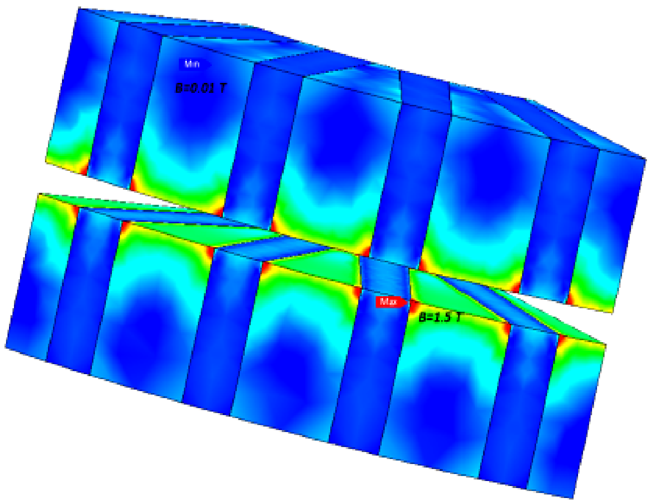
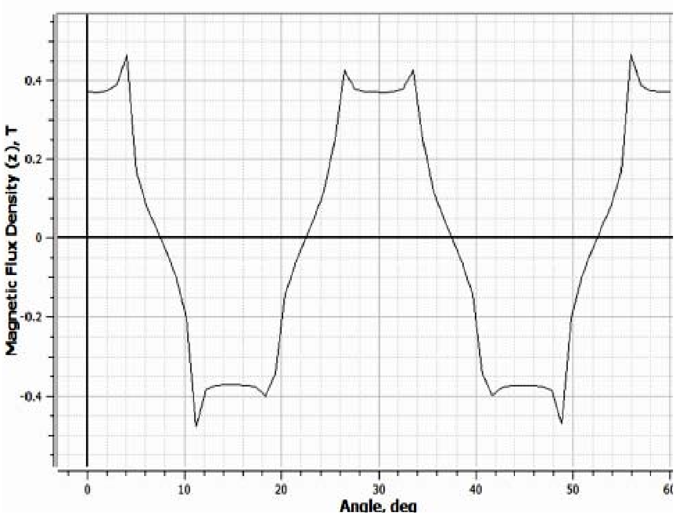
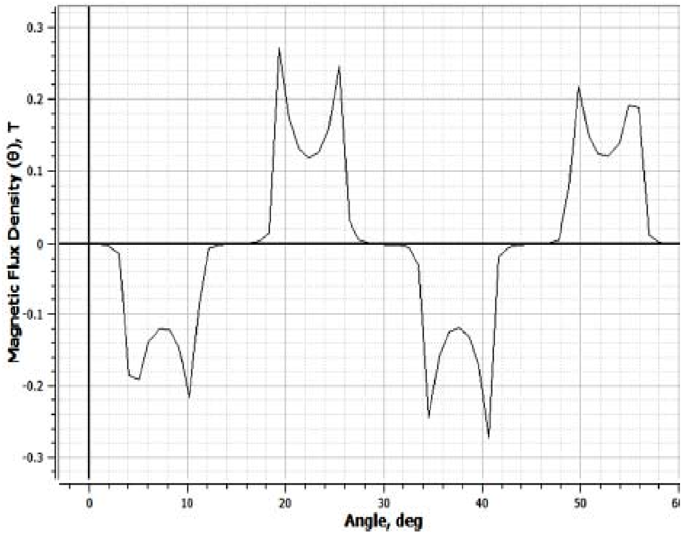


Fig. 3. Rotor-PM flux density distribution in the two outer-rotor disks of the new double-sided AFPM micro-wind generator.



(a)



(b)

Fig. 4. Axial (a) and circumferential (b) components of the flux density in the airgap close to the coreless-stator surface of the new double-sided AFPM micro-wind generator.

III. FINITE-ELEMENT FIELD ANALYSIS FOR DESIGN EVALUATION OF THE NOVEL DOUBLE-SIDED AFPM MICRO-WIND GENERATOR

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 novel double-sided AFPM micro-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 new double-sided AFPM micro-wind generator is presented in Fig. 3, which proves that magnetic saturation in the PM-rotor disks is not of concern, since a maximum value of 1.5 T has been achieved.

Axial and circumferential components of the magnetic flux density in the airgap, near the coreless-stator surface, are plotted in Fig. 4, as obtained from 3-D FE analysis.

The performance of the new double-sided AFPM micro-wind generator supplying an isolated, three-phase resistive load is computed using the 3-D FE time-stepping analysis. Fig. 5 presents the FE-computed dynamic electromagnetic torque. The peak-to-peak value of dynamic torque ripple is less than 5% from the rated torque, as it only consists in the mutual torque ripple caused by the 6th-harmonic component of the developed electromagnetic torque.

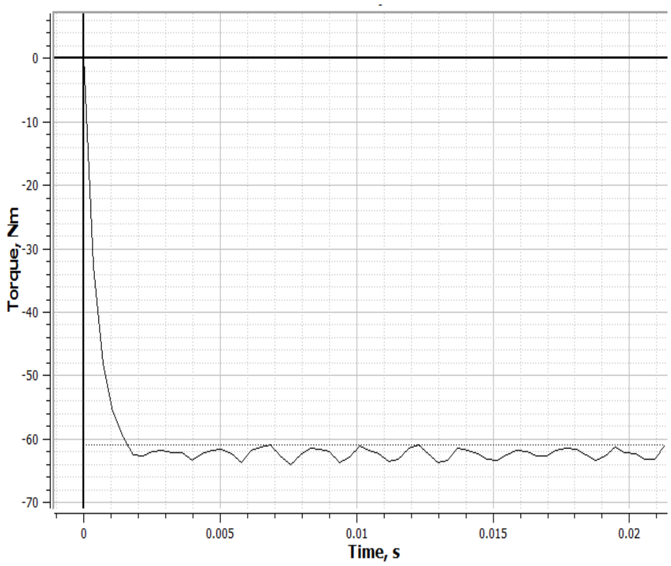
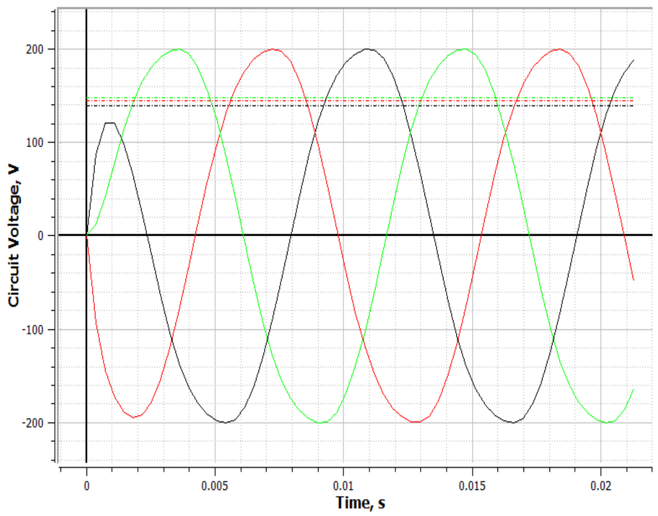
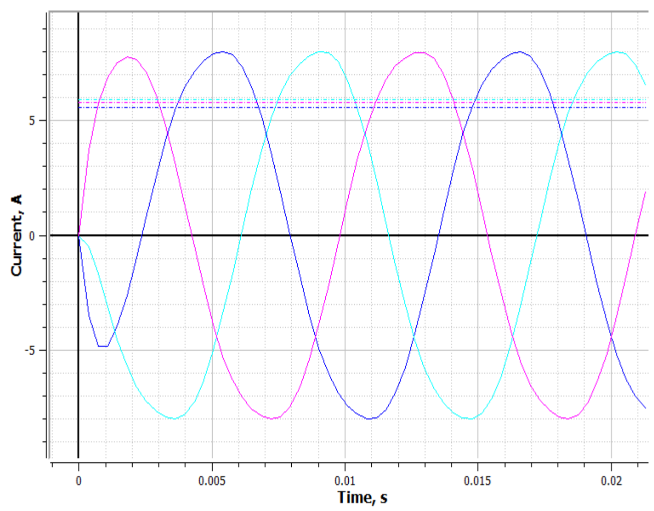


Fig. 5. Dynamic electromagnetic torque of the new double-sided AFPM wind-generator under resistive load condition.



(a)



(b)

Fig. 6. Stator-winding phase-voltage (a) and phase-current (b) waveforms for the new double-sided AFPM wind-generator under resistive load condition.

Fig. 6 shows the computed stator-winding phase-voltage and phase-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.

The FE-computed results, as well as the active material masses for the design analysis of the new double-sided AFPM micro-wind generator are summarized in Table II. It must be pointed out that for efficiency estimation only stator-winding copper losses have been considered.

TABLE II
DESIGN ANALYSIS RESULTS FOR THE NEW DOUBLE-SIDED INNER-CORELESS-STATOR AFPM MICRO-WIND GENERATOR

Design analysis result	**Value**
Mass of rotor disks (with rotor PMs) [kg]	32.4
Mass of rotor PMs [kg]	18
Copper mass of the stator-winding [kg]	3.84
Total mass [kg]	54.24
$I_{ph\,rms}$ [A]	5.7
$U_{ph\,rms}$ [V]	145
Stator-winding copper losses [W]	349.1
Torque [Nm]	61.8
Efficiency [%]	89

IV. CONCLUSION

A new design of the double-sided inner-coreless-stator AFPM wind-generator has been proposed and discussed in this paper. Its outer PM-rotor disk structure with embedded rectangular-shaped PMs, having alternating circumferential magnetization, and interspersed iron pieces in flux-concentration arrangement, combined with coreless-stator non-overlapping concentrated winding make this design well suited for low-speed micro-wind generator applications. FE-based design analysis results have shown its good performances in output characteristics, electromagnetic torque, energy efficiency and cost savings.

ACKNOWLEDGEMENT

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