Analysis of Innovative Design Variations for Double-Sided Coreless-Stator Axial-Flux Permanent-Magnet Generators in Micro-Wind Power Applications

M. Chirca, S. Breban, C.A. Oprea, M.M. Radulescu

***Abstract* -- An analysis of variations of innovative design for double-sided inner-coreless-stator axial-flux permanent-magnet (AFPM) generators intended for micro-wind turbine applications is presented in this paper. The 3-D finite-element field analysis proves that design variations of ironless stator with non-overlapping concentrated winding, sandwiched between two opposing steel rotor disks with embedded circumferentially-magnetized ferrite permanent magnets (PMs) in flux-concentration arrangement, may represent good-performance and cost-effective double-sided topologies for AFPM machines in micro-wind power generation applications.**

***Index Terms*–Axial-flux generator, concentrated windings, direct drive, ironless stator, finite element analysis, permanent-magnet synchronous generator, wind energy conversion systems.**

I. INTRODUCTION

Axial-flux permanent-magnet (AFPM) generators are increasingly being used in the last decade for direct-drive micro-wind turbine applications [1, 2]. 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, which make them particularly suitable for mechanical integration with wind turbines. Direct-driven micro-wind generators have to operate at very low speeds in order to match the micro-wind-turbine speed, and to produce electricity within a reasonable frequency range (25–70 Hz); hence, they have a rather big size, and must be designed with a large number of poles.

The drawback of the low-speed direct-driven AFPM wind-generator is that it requires larger diameter, which affects the material cost of the machine [3]. However, by adopting innovative design configurations for the wind generators, the overall cost of micro-wind turbine systems can be significantly lowered; moreover, the manufacturing and maintenance processes may be simplified, and the complexity of the required equipment may be reduced.

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 [4, 5]. It has the highest torque production capability due to the higher volume of PM material used. As the magnetic losses in rotor PMs and disks are very small and can be neglected, the rotor disks can be manufactured from solid iron. 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 disadvantage of inherent risk 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 essential 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 bending of the rotor disks with the consequence of closing the running clearance between stator and rotor, as well as deteriorating the cooling capacity. However, spacers tapered at both ends of the wind generator may ensure that the effective airgap between the rotor disks remain constant.

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 easy 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 external 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, and hence eddy-current losses, in the stator-winding conductors,

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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, the innovative design of double-sided inner-coreless-stator AFPM machines for use as direct-driven generators with residential micro-wind turbines is proposed and discussed. Section III presents the 3-D finite-element analysis of innovative design variations for double-sided inner-coreless-stator AFPM micro-wind generators. Conclusion is drawn in Section IV.

II. BASIC INNOVATIVE DESIGN FOR DOUBLE-SIDED CORELESS-STATOR AFPM MICRO-WIND GENERATOR

The basic 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 a few 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 generator is directly driven by the wind 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 coupling to isolated loads [6].

The proposed topology of the double-sided inner-coreless-stator AFPM wind-generator is shown in Fig.1. It provides an innovative 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 extended to increase the magnetic flux linkage of the machine;
- 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.

The stator winding considered for the new double-sided inner-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 positive features of this coreless (airgap) winding layout are the reduced overall axial length of the machine, the shorter length of the end-windings, the lower total volume of copper used and, thus, the reduced stator-winding copper losses.

The coreless-winding stator is cast with composite material of epoxy resin and hardener to build the disk-shape structure. The use of round wire in the winding-coil is preferred due to its low cost and availability, but with the penalty of a low coil-filling factor. By axial twisting of multi-stranded wires, the eddy-current loss component of copper losses in the stator winding is minimized [3, 4].

The main data for the basic innovative design of double-sided inner-coreless-stator AFPM wind-generator are given in Table I.

Table I
Main data for the basic innovative design
of double-sided inner-coreless-stator AFPM wind-generators

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 clearance [mm]	2
PM remanence [T]	0.4
Number of stator-winding phases	3

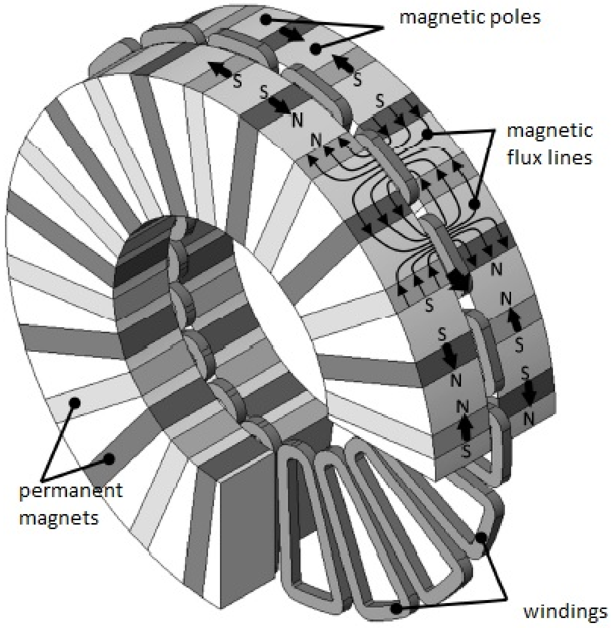

Fig. 1. Basic innovative design of the double-sided inner-coreless-stator AFPM wind generator.

III. FINITE-ELEMENT ANALYSIS OF BASIC INNOVATIVE DESIGN VARIATIONS FOR DOUBLE-SIDED INNER-CORELESS-STATOR AFPM MICRO-WIND GENERATORS

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 basic innovative design for the double-sided inner-coreless-stator AFPM micro-wind generator is depicted in Fig. 3, which proves that magnetic saturation in the PM-rotor disks is not of concern, since maximum value of 1.5 T has been achieved.

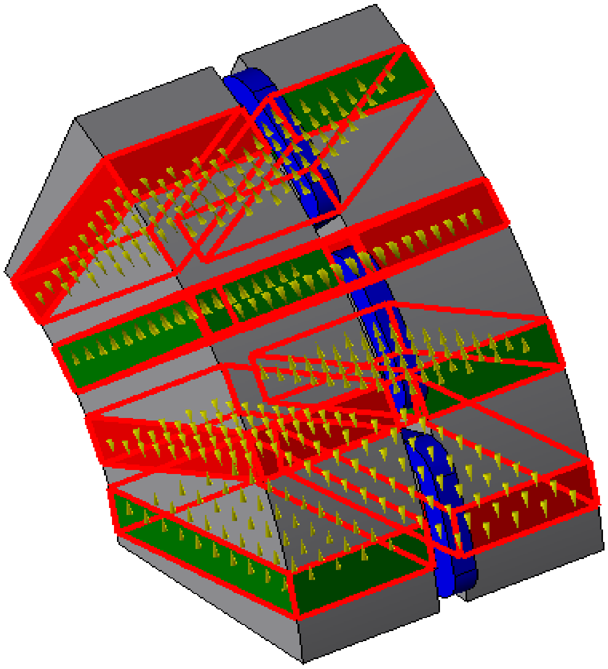

Fig. 2. Flux-concentration arrangement of embedded circumferentially-magnetized PMs on the two outer-rotor disks of the basic innovative design for the double-sided inner-coreless-stator AFPM wind generator.

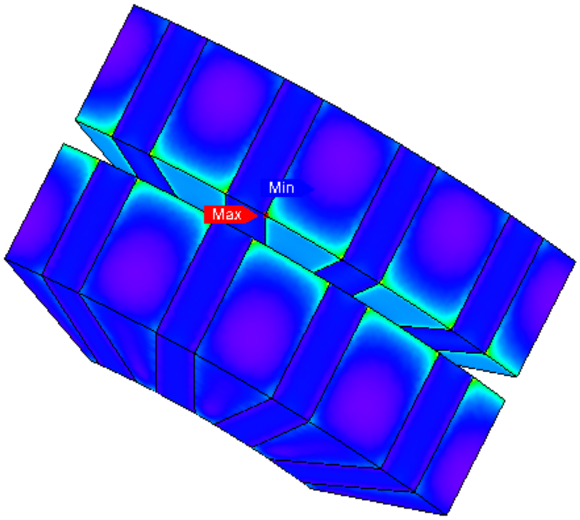

Fig. 3. Rotor-PM flux density distribution in the two outer-rotor disks of the basic innovative design for the double-sided inner-coreless-stator AFPM wind generator

The performance of the basic innovative design for the double-sided inner-coreless-stator AFPM micro-wind generator supplying an isolated, three-phase resistive load is computed using the 3-D FE time-stepping analysis.

Fig. 4 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.

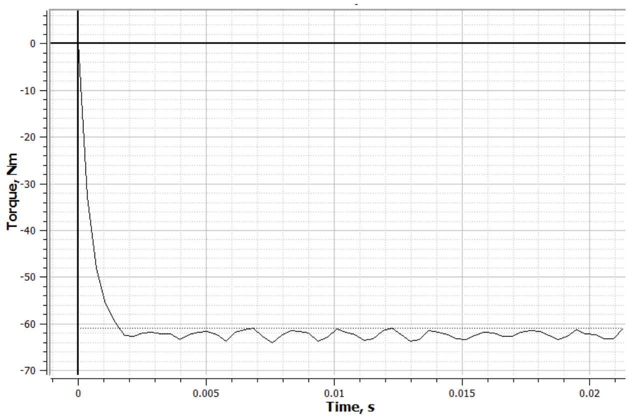

Fig. 4. Dynamic electromagnetic torque of the new double-sided AFPM wind-generator under resistive load condition.

Fig. 5 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.

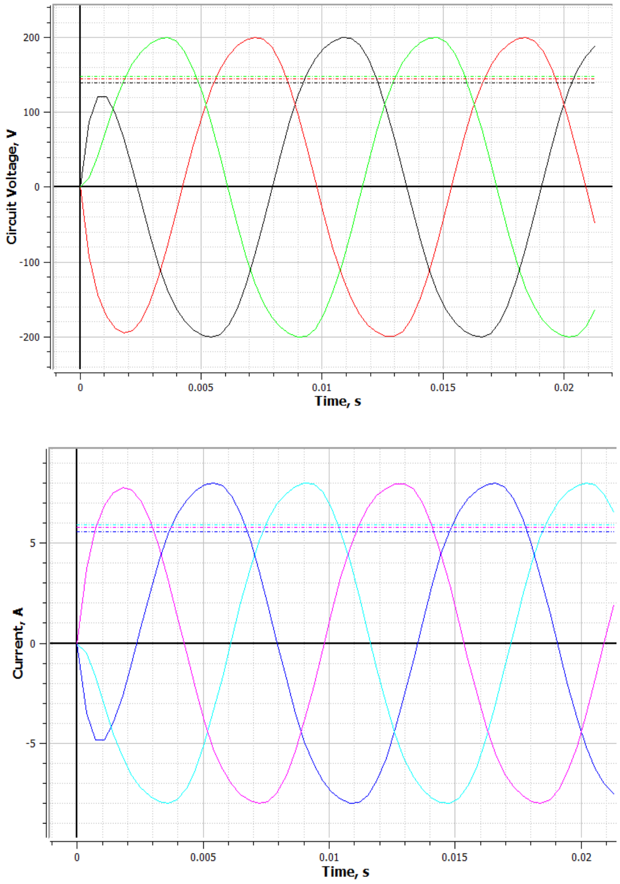

Fig. 5. Stator-winding phase-voltage and phase-current waveforms for the new double-sided AFPM wind-generator under resistive load condition.

The FE-computed results for the basic innovative design of the double-sided inner-coreless-stator AFPM micro-wind generator, running at the rated speed of 480 [rpm], are summarized in Table II. It must be pointed out that for efficiency estimation only stator-winding copper losses have been considered.

Table II
FE-analysis results for the basic innovative design of double-sided inner-coreless-stator AFPM wind-generators

Design analysis result	Value
Stator thickness [mm]	10
Inner diameter [mm]	170
Copper mass of the stator-winding [kg]	4.6
I_{ph}rms [A]	4.9
U_{ph}rms [V]	174
Stator-winding copper losses [W]	334
Efficiency [%]	89.94

The first variation of the basic innovative design for the double-sided inner-coreless-stator AFPM micro-wind generator accounts for the modification of the stator thickness (axial length) from 10 [mm] to 8, 9, 11 and 12 [mm]. The corresponding FE-computed results for this innovative design variation of the double-sided inner-coreless-stator AFPM micro-wind generator, running at the rated speed of 480 [rpm], and supplying the same three-phase resistive load, are given in Table III.

Table III
FE-analysis results for the first variation of the basic innovative design for double-sided inner-coreless-stator AFPM wind-generators

Design analysis result	Value			
Stator thickness [mm]	8	9	11	12
Inner diameter [mm]	170	170	170	170
Copper mass of the stator-winding [kg]	3.8	4.2	5	5.4
$I_{ph\mathrm{rms}}$ [A]	5.2	5.1	4.8	4.8
$U_{ph\mathrm{rms}}$ [V]	167	171	175	176
Stator-winding copper losses [W]	295	318	354	377
Efficiency [%]	90.95	90.4	89.3	88.82

As second variation of the basic innovative design for the double-sided inner-coreless-stator AFPM micro-wind generator, it is considered the modification of the stator thickness (axial length) from 10 [mm] to 8, 9, 11 and 12 [mm], as well as the reduction of the inner diameter from 170 [mm] to 150 [mm]. The corresponding FE-computed results for this innovative design variation of the double-sided inner-coreless-stator AFPM micro-wind generator, running at the rated speed of 480 [rpm], and supplying the same three-phase resistive load, are summarized in Table IV.

Comparative 3-D FE analysis results of Tables II-IV reveal that the basic innovative design variations, i.e. the stator thickness of 8 [mm] and the inner diameter of 150 [mm], give the best efficiency at low overall costs for double-sided inner-coreless-stator AFPM generators suitable to micro-wind turbine applications.

Table IV
FE-analysis results for the second variation of the basic innovative desig for double-sided inner-coreless-stator

Design analysis result	Value				
Stator thickness [mm]	8	9	10	11	12
Inner diameter [mm]	150	150	150	150	150
Copper mass of the stator-winding [kg]	4	4.5	5	5.5	6
I_{ph}rms[A]	5	4.88	4.82	4.6	4.5
U_{ph}rms[V]	185	190	193	195	196
Stator-winding copper losses [W]	268	287	313	322	339
Efficiency [%]	91.8	91.5	90.9	90.6	90.1

IV. CONCLUSION

In this paper, the 3-D FE analysis of innovative design variations for double-sided inner-coreless-stator AFPM generators intended for use in micro-wind turbine applications has been carried out.

The analysis proves that design variations of outer PM-rotor disks with embedded rectangular-shaped ferrite-PMs, having alternating circumferential magnetization, and interspersed iron pieces, in flux-concentration arrangement, combined with coreless-stator non-overlapping concentrated winding make such AFPM machine topologies well suited for low-speed micro-wind generator applications.

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BIOGRAPHIES

Mihai Chirca obtained the bachelor degree from the Technical University of Cluj-Napoca, Romania, in 2009. Electric machines design has become a familiar domain, mostly thanks to the experience gained in the bachelor and master theses elaboration. Both works were focused on designing generators for electrical systems that provide electricity using renewable sources of energy. The master thesis was elaborated at the Darmstadt University of Technology, Germany during the European student program ERASMUS. He is currently with the Department of Electric Machines and Drives, Technical University of Cluj-Napoca, Romania, as a Ph.D. student.

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Mircea M. Radulescu received the Dipl.-Ing. degree with honors from the Technical University of Cluj-Napoca, Romania, in 1978 and the Ph.D. degree from the Polytechnic University of Timisoara, Romania, in 1993, both in electrical engineering. Since 1983, he has been with the Faculty of Electrical Engineering, Technical University of Cluj-Napoca, Romania, where he is currently a Full Professor in the Department of Electric Machines and Drives, as well as the Head of the Special Electric Machines and Light Electric Traction (SEMLET) Research Laboratory.

He is author or co-author of more than 150 published scientific papers in refereed technical journals and international conference and symposium proceedings. His teaching and research activities include computer-aided design of electromechanical devices; field analysis of electromagnetic structures; design and control of small electric motors; actuators and mechatronic drives; light electric traction systems.