Comparative Design Analysis of Ferrite-Permanent-Magnet Micro-Wind Turbine Generators

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Abstract – **This paper investigates two topologies of ferrite-permanent-magnet synchronous machines for use as direct-driven generators in micro-wind power applications, i.e. the axial-flux double-sided inner-stator permanent-magnet (AF-PM) generator and the radial-flux spoke-type interior-permanent-magnet (RF-IPM) generator. The comparative design analysis of AF-PM and RF-IPM micro-wind generators based on finite-element field analysis proves that both topologies represent a good-performance and cost-effective solution of choice for micro-wind power applications.**

Index Terms – **wind energy conversion system, direct drive, ferrite-permanent-magnet wind generator, axial-flux generator, radial-flux generator, finite-element field analysis**

I. INTRODUCTION

Small-scale wind energy conversion systems are an attractive choice to generate electric power in urban and rural areas, where the installation of the distribution network is not economically rational. For stand-alone micro-wind power applications, the use of permanent-magnet machines as direct-driven turbine generators has been intensively studied. Despite their great potential, micro-wind turbine generators reveal low penetration in the renewable energy production market, mainly due to their high cost, which vary from €2,500 to €6,000 per installed kW. Their low energy yield represents another reason, since they operate mostly in low and moderate wind-speed areas. Since small wind turbines are usually self-starting, they rely on the torque produced by the wind acting on the blades in order to start, thus poor starting is another issue affecting the energy yield. Moreover, micro-wind turbines require good technical skills and rather complex equipment in manufacturing and maintenance processes, which increase their installing and operational costs [1].

By using direct-driven wind generators, one of the less reliable mechanical components is eliminated, thus reducing the size of the entire system, lessening noises and lowering installation and maintenance costs. However, 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 (25-90 Hz); hence, the micro-wind generator has a rather big size, and must be designed with a large number of poles [2].

The instability of rare-earth permanent-magnet prices and the insecurity of the supply of raw materials needed for neodymium-iron-boron magnets have led to the use of ferrite magnets as an alternative in designing affordable permanent-magnet micro-wind generators [3, 4].

In this paper, two designs of ferrite-permanent-magnet generators for micro-wind power applications are proposed and compared using the finite-element (FE) magnetic field analysis; the first design is of axial-flux type, while the second one is of radial-flux type.

The paper is organized as follows. In Section II, the design of an axial-flux (AF) double-sided inner-stator ferrite-permanent-magnet (FPM) micro-wind generator is presented and evaluated by means of 3-D FE field analysis. In Section III, the alternative design of a radial-flux (RF) spoke-type interior-FPM micro-wind generator is addressed, and its performance is investigated using 3-D FE simulation results. Comparative design analysis results for both ferrite-permanent-magnet micro-wind generators are discussed in Section IV, and some concluding remarks are drawn at the end of the paper.

II. DESIGN ANALYSIS OF THE DOUBLE-SIDED INNER-STATOR AF-FPM MICRO-WIND GENERATOR

The innovative design of a double-sided inner-coreless-stator AF-FPM micro-wind generator, proposed in [5] and displayed in Fig.1, provides an outer FPM-rotor-disk structure with embedded rectangular-shaped FPMs, having alternating circumferential magnetization, and interspersed iron pieces, constituting the rotor magnetic poles. This flux-concentration arrangement offers the following benefits: (i) the flux density in the magnetic poles is higher than in the FPMs; (ii) the axial length of the micro-wind generator may be extended to increase its magnetic flux linkage; (iii) the effective airgap is reduced due to embedded (not surface-mounted) rotor-FPMs.

The stator winding considered for this double-sided inner-coreless-stator AF-FPM micro-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 proposed topology is further subjected to design optimization in order to maximize the efficiency of the micro-wind generator, while ensuring its rated output power. Only four variables of the machine parameters are taken into account during the optimization process. These are the rotor-disk inner
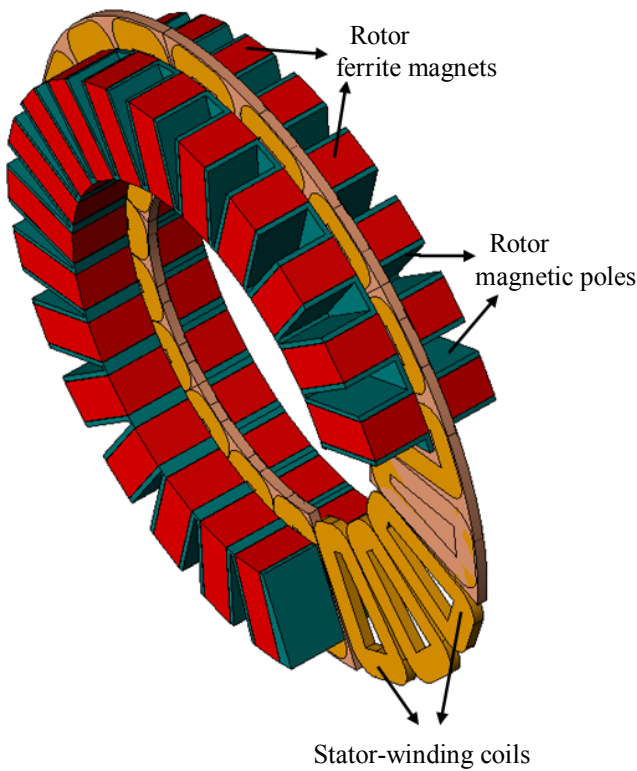
Fig. 1. Design features of the double-sided inner-coreless-stator AF-FPM micro-wind generator.

radius, the FPM thickness and width to pole pitch ratios and the total axial length of the machine.

The main data of the optimized design of the double-sided inner-coreless-stator AF-FPM micro-wind generator are listed in Table I.

Table I
Main optimized-design data of the double-sided
inner-coreless-stator AF-FPM micro-wind generator

Design data	Value
Number of poles	24
Number of coils	18
Inner diameter [mm]	240
Outer diameter [mm]	360
Stator thickness [mm]	6
Rotor-disk thickness [mm]	35
Axial length [mm]	78
Airgap clearance [mm]	2
PM remanence [T]	0.4

The disadvantage of the double-rotor AF-FPM topology is the strong magnetic attractive force between the two opposing PM rotor disks, which can cause the deflection of the rotor disk with the consequence of closing the running clearance between stator and rotor, as well as deteriorating the cooling capacity. The forces on the magnetic poles were calculated analytically and also FE-computed, and both results were in the range of 700 N per rotor magnetic pole.
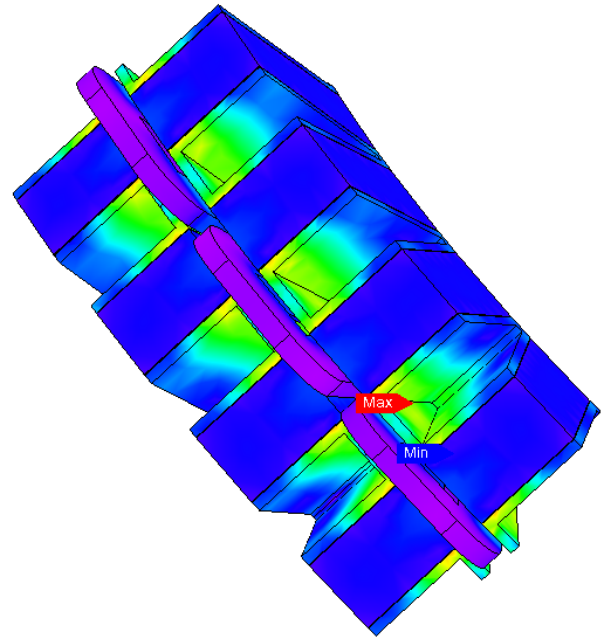

Fig. 2. Rotor-PM flux density distribution in the two outer-rotor disks of the double-sided inner-coreless-stator AF-FPM micro-wind generator.

Rotor-PM flux-density distribution from 3-D FE analysis of the double-sided AF-FPM micro-wind generator is presented in Fig. 2, which proves that magnetic saturation in the PM-rotor disks is not of concern, since a maximum value of 1.6 T has been achieved.

The stator winding considered for the proposed double-sided inner-coreless-stator AF-FPM micro-wind generator has non-overlapping concentrated-winding topology, for which the coils lie entirely next to each other in the same plane. The benefits of this coreless-winding layout are reduced overall axial length of the machine, shorter length of the end-windings, lower total volume of copper and, thus, reduced stator-winding copper losses [6 – 8].

The design analysis of the double-sided inner-coreless-stator AF-FPM micro-wind generator and its performances by supplying an isolated resistive load of 50 Ω are carried out comparatively through experiments on the built prototype, shown in Fig. 3, and by using magnetic field FE-computations.

Fig. 4 presents the experimentally-obtained and the FE-computed dynamic electromagnetic torque of the double-sided inner-coreless-stator AF-FPM micro-wind generator.

The peak-to-peak value of dynamic torque ripple is less than 4% from the rated torque in both experimental and computed results.

Experimentally-obtained on built prototype and FE-computed stator-winding phase-voltage and phase-current waveforms at resistive load for the double-sided inner-coreless-stator AF-FPM micro-wind generator under consideration are practically sinusoidal, as shown in Fig. 5. It is to be noted, that the FE-computed waveforms have taken into account the geometry of the stator-armature winding coils.
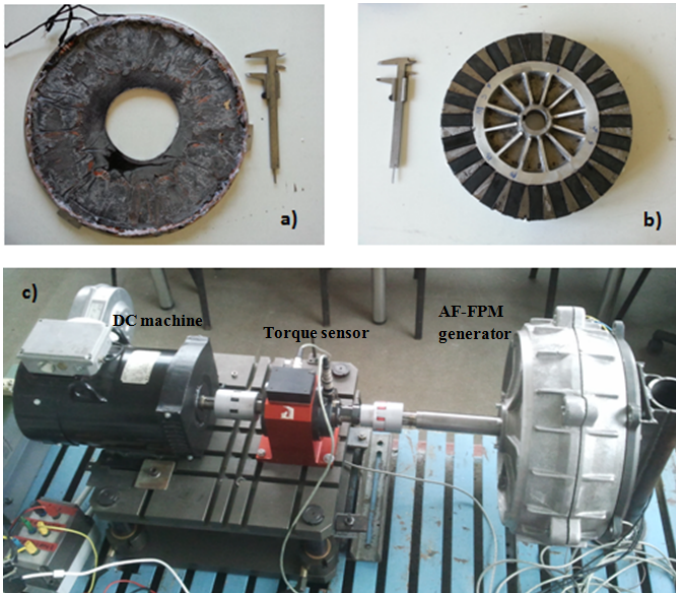
Fig. 3. (a) Coreless-winding stator cast with composite material of epoxy resin; (b) Rotor disk with FPMs; (c) Testing set-up of the built prototype AF-FPM generator.
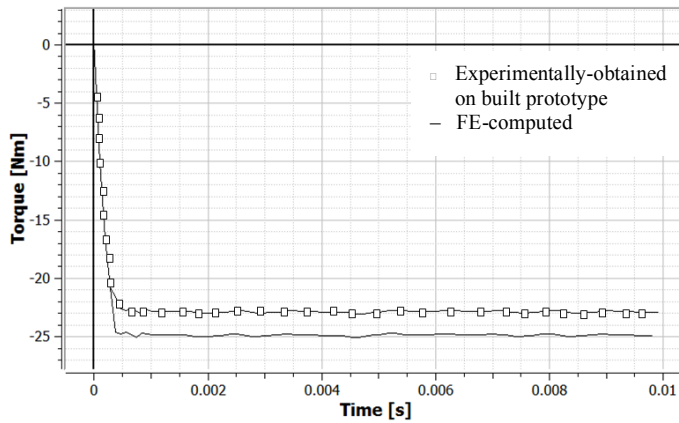

Fig. 4. Dynamic electromagnetic torque of the double-sided inner-coreless-stator AF-FPM micro-wind generator under resistive load condition.

The magnetic losses in the rotor FPMs and cut-up iron disks are very small, and can be neglected, as there is no change in the magnetic flux direction in the rotor back-iron. Moreover, eddy-current losses in the rotor FPMs are insignificant due to the high resistivity of ferrite bulk material.

III.   DESIGN ANALYSIS OF THE RF SPOKE-TYPE INTERIOR-FPM MICRO-WIND GENERATOR

The alternative topology of micro-wind generator considered in this paper is the radial-flux (RF) one with interior-FPM rotor (Fig. 6). Its design is addressed using the commercial software SPEED, a specialized design tool for electric machines, firstly developed at the University of Glasgow, UK.
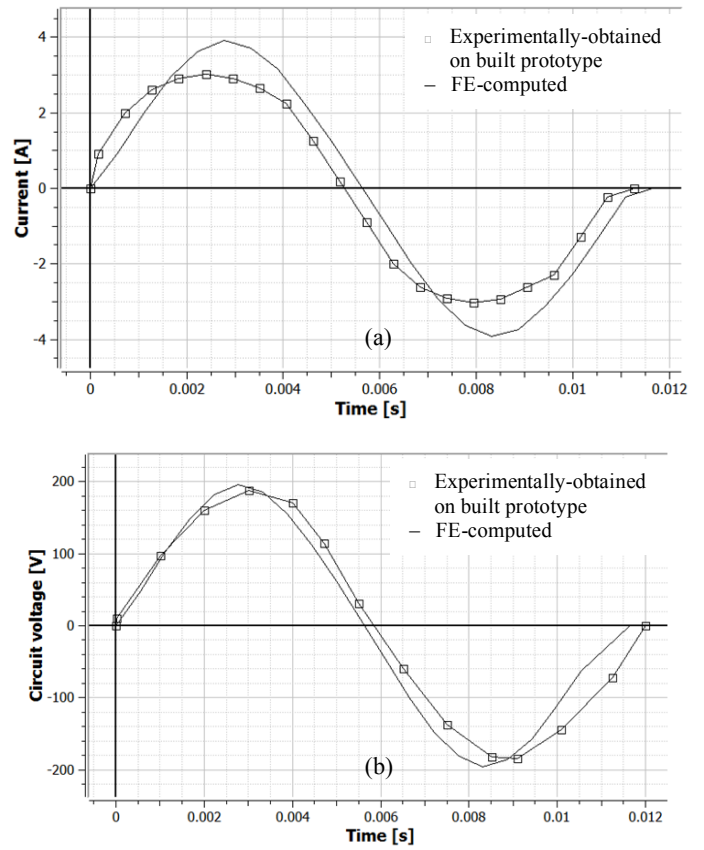

Fig. 5. Stator-winding phase-current (a) and phase-voltage (b) waveforms for double-sided AFPM wind-generator under resistive load condition.
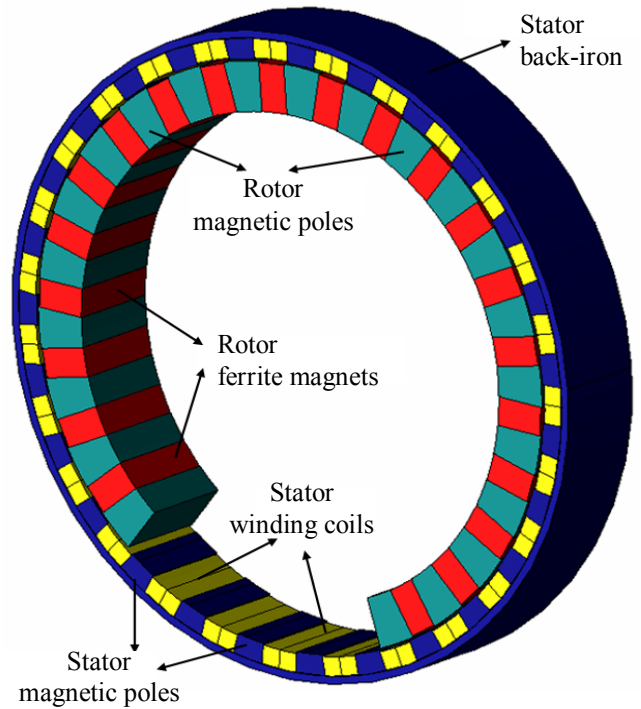

Fig. 6. Design features of the RF spoke-type interior-FPM micro-wind generator.

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Due to their low remanence, FPMs require some kind of flux concentrating scheme to achieve acceptable airgap flux densities. One possibility is to bury FPMs inside the rotor core in a spoke-type configuration, i.e. FPMs with alternating tangential magnetization are placed with pole shoes in between; hence, the magnetic flux lines from the FPMs are concentrated in the rotor poles and forced towards the airgap [9 – 11].

Static simulations were performed using SPPED software, and various geometric dimensions were modified in order to obtain the better micro-wind generator design in terms of delivered electric power, output voltage and energy efficiency. The main data of the optimized design of the RF spoke-type interior-FPM micro-wind generator are given in Table II.

Table II
Main optimized-design data of the RF spoke-type
interior-FPM micro-wind generator

Design data	Value
Number of rotor poles	26
Number of stator coils	27
Inner diameter [mm]	300
Outer diameter [mm]	395
Stator back-iron thickness	6
Stator thickness [mm]	13
Rotor thickness [mm]	30
Axial length [mm]	60
Airgap clearance [mm]	1
PM remanence [T]	0.4

Once structurally optimized, the RF spoke-type interior-FPM micro-wind-generator model has been exported to JMAG-Designer for design evaluation using FE field analysis. The magnetic flux density distribution in the micro-wind generator structure under resistive load condition is displayed in Fig. 7, showing symmetrical flux line paths in the stator core for values up to 1.8 [T].
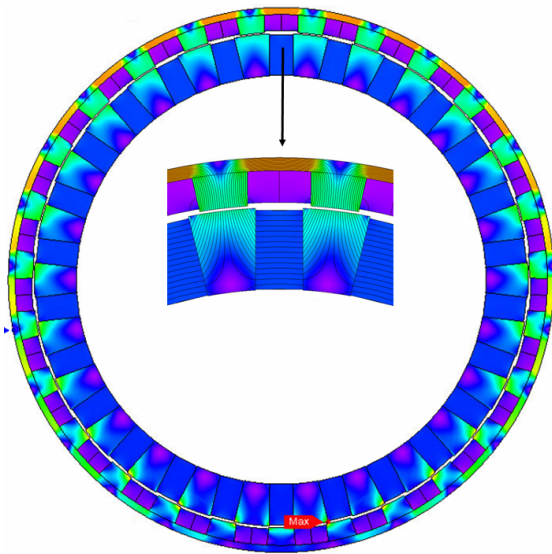

Fig. 7. Magnetic flux density distribution in the RF spoke-type interior-FPM micro-wind generator under resistive load condition.

The RF spoke-type interior-FPM micro-wind-generator has 27 stator concentrated-coils and poles, and 26 rotor poles. This configuration leads to a very low cogging (or detent) torque. In Fig. 8, the FE-computed cogging torque waveform is shown, proving that it represents only 0.4% from the rated electromagnetic torque.

The performances of the RF spoke-type interior-FPM micro-wind generator feeding an isolated resistive load are analyzed using FE simulations. Fig. 9 shows the FE-computed dynamic electromagnetic torque.

FE-computed stator-winding phase-voltage and phase-current waveforms under resistive load are presented in Fig. 10.

The FE-computed results for the optimized design analysis of the RF spoke-type interior-FPM micro-wind generator are obtained at the rated speed of 450 [rpm].
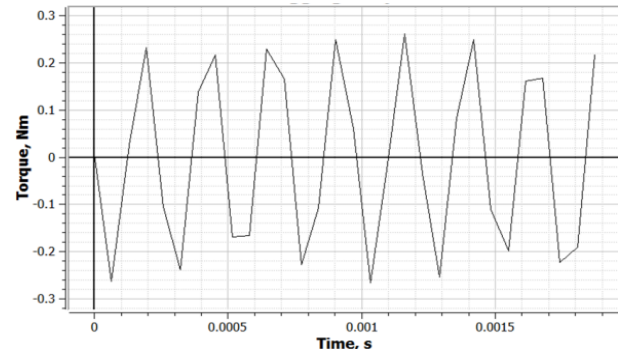

Fig. 8. FE-computed cogging torque waveform
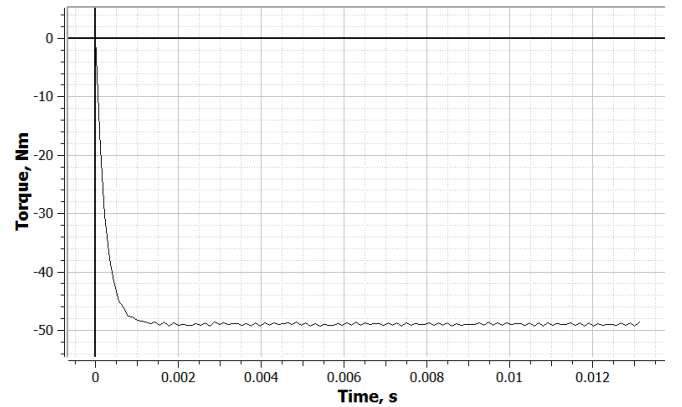for the RF spoke-type interior-FPM micro-wind generator.

Fig. 9. FE-computed dynamic electromagnetic torque
of the RF spoke-type interior-FPM micro-wind generator
under resistive load condition.

IV. COMPARATIVE DESIGN ANALYSIS RESULTS

The main comparative design analysis results are listed in Table III, together with some dimensional parameters for both FPM micro-wind generators under study. The estimated costs of the active materials, i.e. copper, FPM and iron, are given. The reference price for the active parts is 3 Euro/kg for FPMs, 8 Euro/kg for copper and 4 Euro/kg for stator/rotor iron. These
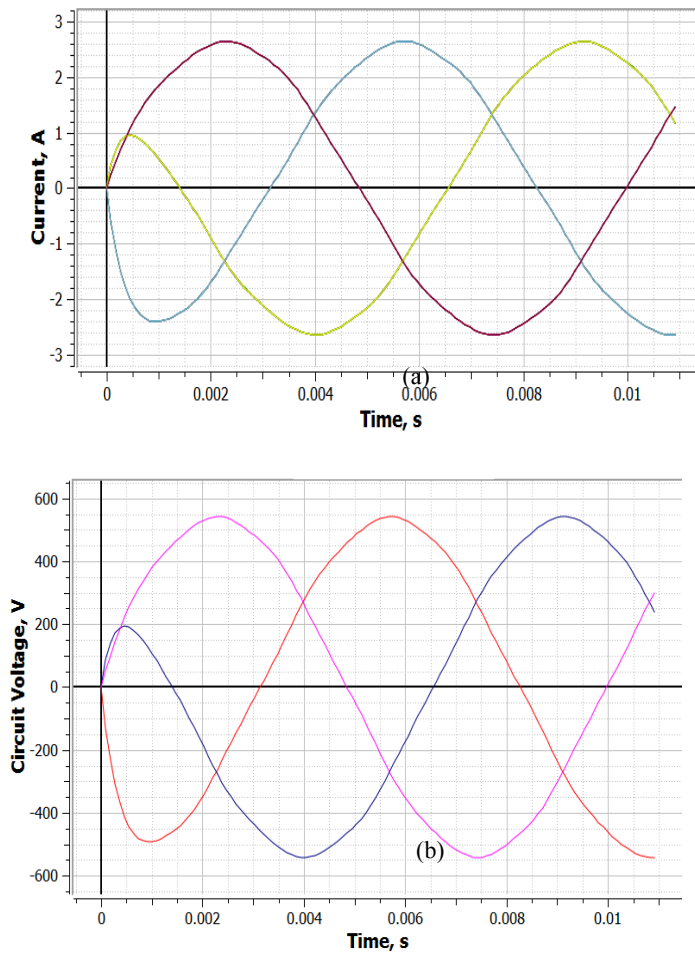
Fig. 10. Stator-winding phase-current (a) and phase-voltage (b) waveforms for the RF spoke-type interior-FPM micro-wind generator under resistive load condition.

Table III
Comparative design analysis results
for both FPM micro-wind generators

Parameter	Value	
Micro-wind generator topology	**AF-FPM**	**RF interior-FPM**
Copper weight	3.5 kg	7 kg
FPM weight	11.1 kg	5.3 kg
Iron weight	6.3 kg	8.4 kg
Total weight	20.9 kg	20.7 kg
Efficiency	91 %	89.8 %
Turns per coil	120	165
Phase resistance	3.8 ohm	5.52 ohm
Airgap clearance	2 mm	1 mm
Number of stator coils	18	27
Number of rotor poles	24	26
Outer diameter	360 mm	395 mm
Estimated cost of active materials	86.5 Euro	74 Euro
Manufacturing cost factor (K)	1.5	2
Total estimated costs	130 Euro	148 Euro

prices refer only to the raw material without any manufacturing and non-active material costs. The double-sided inner-coreless-stator AF-FPM topology of the micro-wind generator has the highest cost due to FPMs needed for the twin rotors, but is easier to manufacture.

In its turn, the RF spoke-type interior-FPM design has lower estimated mass and cost of active materials. In order to estimate the total cost of the micro-wind generator, the manufacturing cost factor (K) is introduced, as in [12]. Hence, $K = 1.5$, for the double-sided inner-coreless-stator AF-FPM topology, meaning that the manufacturing cost is 50% of the cost of active materials, whereas $K = 2$, for the RF spoke-type interior-FPM structure, due to the more complex manufacturing process.

V. CONCLUSION

In this paper, the comparative design analysis of the double-sided inner-coreless-stator AF-FPM and the RF spoke-type interior-FPM small-scale generator topologies has been carried out. The FE-computed design-analysis results prove that both generator topologies are well suited for low-speed micro-wind power applications.

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