# Optimal Design of a Radial Flux Spoke-Type Interior Rotor Permanent Magnet Generator for Micro-Wind Turbine Applications

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*Abstract* -- **This paper approaches the electromagnetic design and finite-element analysis of a radial flux NdFeB permanent magnet synchronous machine for use as direct-driven generator with low speed micro-wind turbines. The design evaluation of the radial-flux spoke-type permanent magnet (RFPM) generator, based on 2-D and 3-D finite element field analysis, proves that this topology represents a good-performance and cost-effective and could be the machine of choice in grid-connected or stand-alone small-scale wind energy conversion systems.**

*Index Terms*–**Radial-flux generator, direct drive, finite element analysis, permanent-magnet synchronous generator, wind energy conversion systems.**

## I. INTRODUCTION

Nowadays, there is a firm interest regarding the use and development of wind energy conversion systems to generate electric power in urban and rural areas, where the installation of the distributed network is not economically rational. Hence, wind turbines of different rated power are worldwide installed for exploiting the wind power and producing nonpolluting, green energy.

As described in [1], despite their great potential but due to their high cost, which vary from €2,500 to €6,000 per installed kW, micro-wind turbines reveal low penetration in the renewable energy production market. Another reason is represented by their low energy yield, since they operate mostly in low and moderate wind-speed areas. Since micro-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, small-wind turbines require good technical skills and rather complex equipment in manufacturing and maintenance process, which increase their installing and operational costs.

The solution investigated in this paper starts from a preliminary idea that the micro-wind power system should be implemented mostly in urban areas, thus the generator should be very efficient in converting energy at low wind speeds; also for a lower manufacturing and maintenance cost the use of a direct-drive generator is considered. By avoiding the use of mechanical gear box, the less reliable mechanical component is eliminated, thus less noises and the entire system size is reduced. Direct-driven small-wind generators have to operate at very low wind speeds in order to match the turbine speed, and to produce electricity within a reasonable frequency range (25-90 Hz), thus the micro-wind generator requires larger diameter, and must be designed with a large number of poles which affects the material cost of the machine [2]. In [3] - [7] are presented different studies concerning spoke-type electrical machines.

Section II presents the topology of the Radial-Flux Interior PM Generator and its main geometrical and electrical parameters, along with the justification of choosing a spoke-type arrangement for the permanent magnets. In Section III the optimization procedure and the objective function are presented, showing the differences between the initial and optimized structures. Since the structure has 21 coils and 20 poles, 7 three-phase (passive) rectifiers are connected in series to smooth the DC-bus voltage output.

## II. BASIC DESIGN FOR RF SPOKE-TYPE INTERIOR PERMANENT MAGNET MICRO-WIND GENERATOR

Permanent magnet synchronous generators (PMSG) have been an object of numerous research studies with different structures and geometries for different applications. The topology of micro-wind generator considered for this paper is the radial flux interior permanent magnet rotor spoke-type machine.

This topology has radial mounted permanent magnets with alternating circumferential magnetization, buried inside the rotor core and placed between rotor pole shoes, so the magnetic flux lines from the magnets are concentrated in the rotor poles and forced towards the air-gap. Due to this configuration, more magnetic material can be used while keeping the same air-gap radius of the structure or the same volume of magnetic material can be used for a smaller air-gap radius of the generator. It is known that the magnetic flux generated by the arrangement of spoke type permanent magnets is highly concentrated in air gap, thus this design

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topology could produce high power density compared to the other PMSG.

The main data of the optimized design of spoke-type permanent magnet generator are given in Table I.

TABLE I
DESIGN MAIN DATA FOR THE BASIC DESIGN OF SPOKE-TYPE RFPM WIND-GENERATOR.

| Design data | Value |
|---|---|
| Rated power [kW] | 2.5 |
| Rated speed [RPM] | 500 |
| Number of poles | 20 |
| Number of coils | 21 |
| Inner diameter [mm] | 200 |
| Outer diameter [mm] | 310 |
| Stator thickness [mm] | 31.8 |
| Rotor-disk thickness [mm] | 21.8 |
| Axial length [mm] | 40 |
| Airgap clearance [mm] | 1 |
| PM remanence [T] | 1.3 |
| Number of stator-winding phases | 21 |

Once structurally defined, the radial flux spoke-type generator model has been exported to JMAG-Designer for optimization and design evaluation using finite element analysis.

## III. FINITE-ELEMENT ANALYSIS AND DESIGN OPTIMIZATION USING JMAG SOFTWARE

In this paper, the design evaluation of the RF spoke-type interior PM micro-wind generator is conducted by time-stepped 2-D and 3-D finite element (FE) field analysis using the commercial software JMAG-Designer.

Design optimization is made using multi-objective genetic algorithm technique and successfully applied to the RF spoke-type interior PM generator for enhancing its energy efficiency at base speed.

Several constraints on geometrical dimensions, presented in Table II, where applied during the optimization process. They are embedded in the optimized design program, and allow considering only geometrically meaningful design solutions. After 170 evaluation steps, the optimized configuration found for the micro-wind generator under study is presented in Fig.1.

TABLE II
CONSTRAINS OF GEOMETRICAL DIMENSIONS FOR THE OPTIMIZATION PROCESS

| Design variables | Value [mm] | |
|---|---|---|
| | Minimum | Maximum |
| Stator outer diameter [mm] | 140 | 160 |
| Stator inner diameter [mm] | 116 | 130 |
| Stator tooth-width [mm] | 15 | 30 |
| Stator back iron height [mm] | 8 | 20 |
| Rotor pole width [mm] | 12 | 25 |

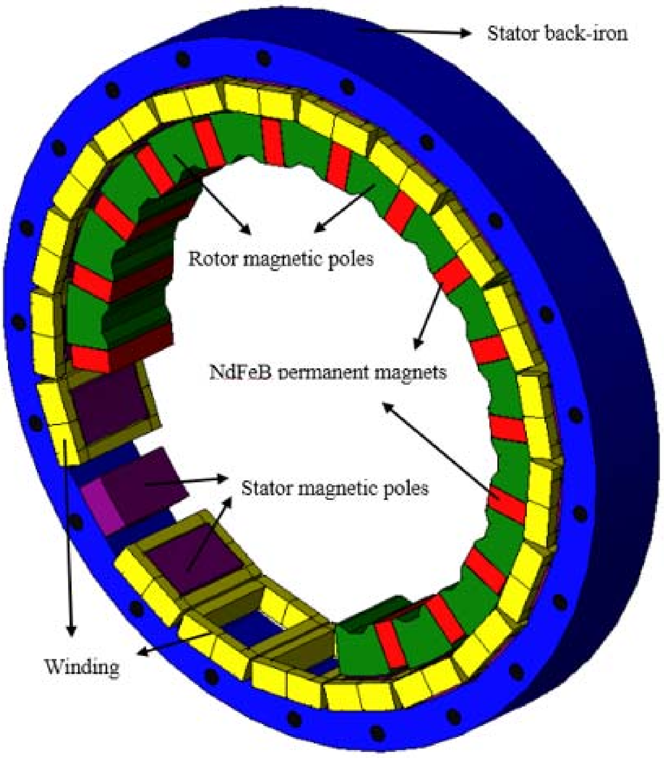

Fig. 1. Design features of the RF spoke-type interior PM wind generator.

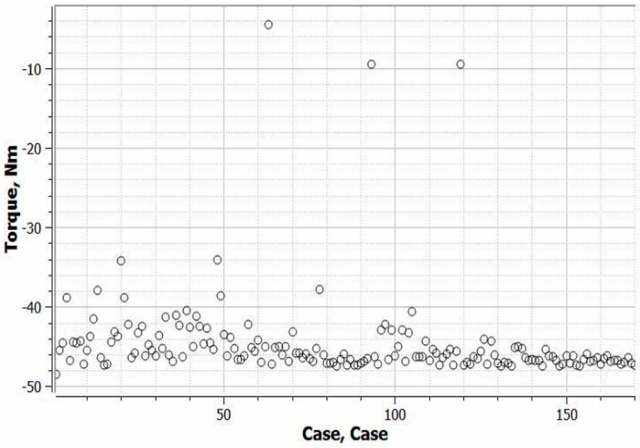

Fig. 2. Torque optimization based on Genetic Algorithm.

The values of torque for all the cases simulated in the optimization phase using the Genetic Algorithm implemented in JMAG software are presented in Fig. 2. The optimization algorithm was set to maximize the following function:

$$f = 0.5\frac{P - Losses}{P} + 0.5\frac{T}{T_i} \tag{1}$$

where,

$P$, is the electrical power generated;

*Losses*, represents the stator and rotor magnetic circuit iron losses, and stator windings Joule losses (PM and mechanical losses where not considered).

$T$, is the estimated electromagnetic torque for each case simulation;

$T_i$, is the electromagnetic torque for the initial design (before optimization).

Design results from the comparison between the initial design and the optimized design are listed in Table III. As one can notice, the optimized design results are good, showing more than 4% higher energy efficiency at base speed for the considered RF spoke-type interior permanent magnet generator. Table IV presents the optimized design generator characteristics.

TABLE III
COMPARISON OF GEOMETRICAL DIMENSIONS AND OTHER PARAMETERS OF THE INITIAL DESIGN AND THE OPTIMIZED DESIGN

| Parameter | Initial design | Optimized design |
|---|---|---|
| Stator outer diameter [mm] | 144 | 155 |
| Stator inner diameter [mm] | 121 | 123 |
| Stator tooth-width [mm] | 21.6 | 23 |
| Stator tooth-height [mm] | 11 | 13.8 |
| Stator back iron height [mm] | 12 | 18 |
| Rotor outer diameter [mm] | 120 | 122 |
| Rotor inner diameter [mm] | 98 | 100 |
| Efficiency [%] | 91.2 | 95.3 |

TABLE IV
OPTIMIZED DESIGN GENERATOR CHARACTERISTICS

| Design analysis result | Value |
|---|---|
| Copper weight [kg] | 0.5 |
| PM weight [kg] | 1.2 |
| Iron weight [kg] | 9 |
| Total weight [kg] | 10.7 |
| Torque [Nm] | 50 |
| $I_{ph\mathrm{rms}}$ [A] | 0.7 |
| $U_{ph\mathrm{rms}}$ [V] | 450 |
| Stator-winding copper losses [W] | 80 |
| Iron losses [W] | 42 |
| Efficiency [%] | 95.3 |

These optimization results show that the multi-objective genetic algorithm succeeds in finding the better design solution. Fig. 3 presents the torque and Joule loss variations with the stator tooth width during the optimization process.

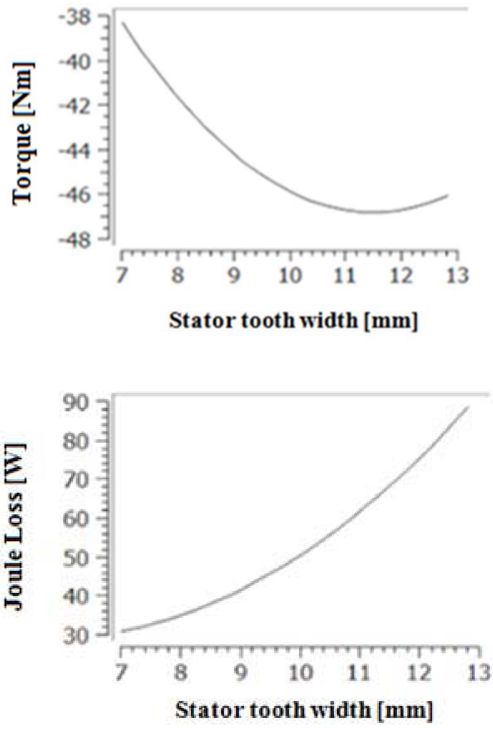

Fig. 3. Torque and Joule loss variations with the stator tooth width.

Stator and rotor-PM flux-density distribution from 2-D finite element analysis design for the RF spoke-type micro-wind generator is depicted in Fig. 4, which proves that magnetic saturation is not of concern, since maximum value of 1.7 T has been achieved.

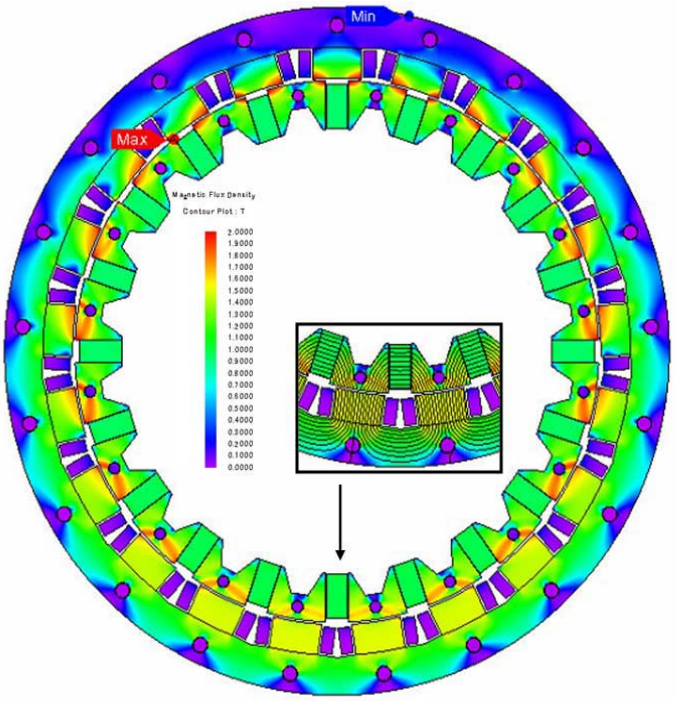

Fig. 4. Magnetic flux density distribution in the RF spoke-type interior PM micro-wind generator under resistive load condition.

The FE-computed results for the optimized design analysis are obtained at the rated speed of 500 rpm. The performances of the RF spoke-type interior-PM micro-wind generator feeding an isolated resistive load are analyzed using FE simulations. The results obtained under 2-D analysis are validated with the results obtained under 3-D analysis. Fig. 5 shows the FE-computed dynamic electromagnetic torque.

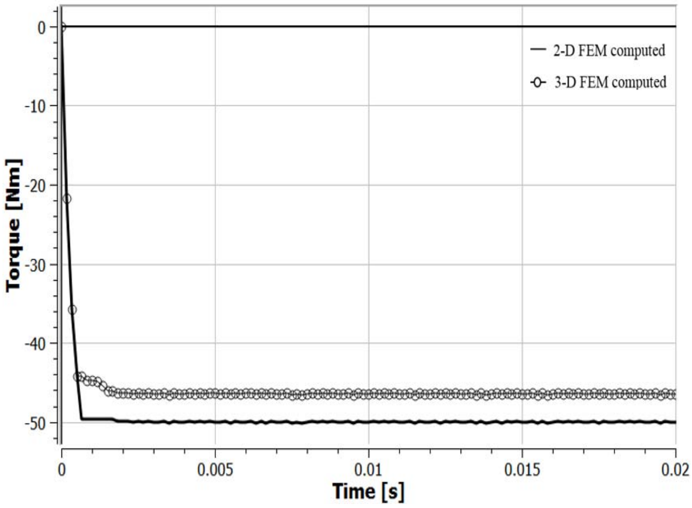

Fig. 5. Dynamic electromagnetic torque of the RF spoke-type interior PM micro-wind generator under resistive load condition.

The 2D and 3D FE-computed stator-winding phase-voltage and phase- current waveform of one of the windings under resistive load are presented in Fig. 6.

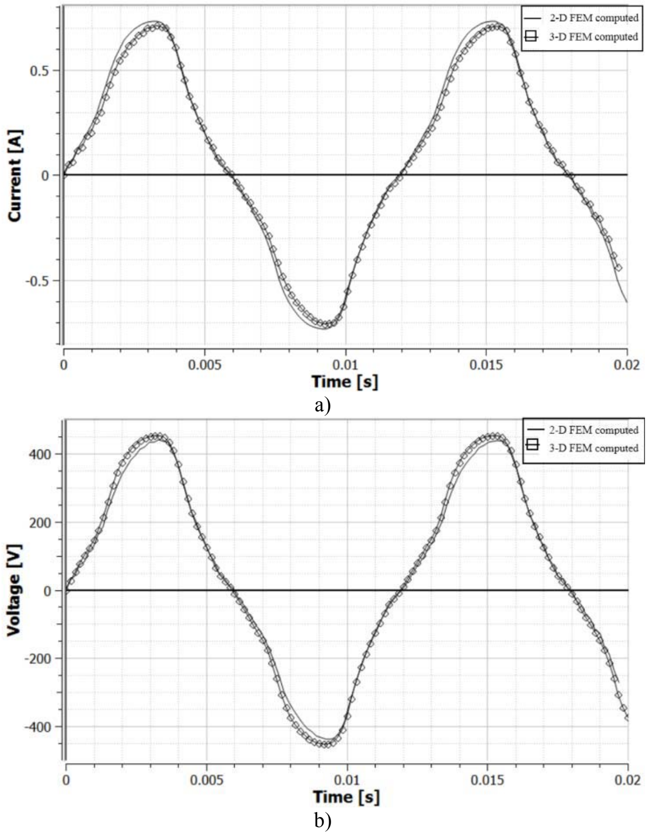

Fig. 6. Stator-winding phase-current (a) and phase-voltage (b) waveforms for RF spoke-type interior PM wind-generator under resistive load condition.

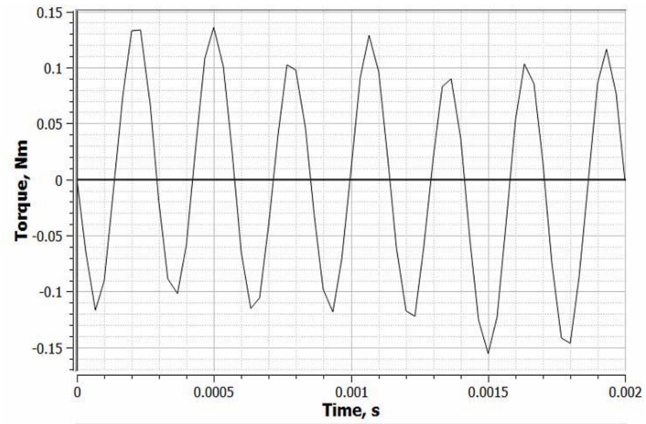

Fig. 7. FE-computed cogging torque waveform for the RF spoke-type interior-PM micro-wind generator.

The micro-wind turbine generator has 21 stator coils and slots, and 20 rotor poles. This configuration gives the possibility to have a very low cogging torque, of approximately 0.2 % (Fig. 7). Also, this configuration of stator-rotor number of poles yields a 21 phase machine, considering that the phases are not grouped in order to obtain a three phase machine.

The rectifier circuit uses 7 three phase series connected diode bridge rectifiers (Fig. 8). The coils are star connected and each of the 7 diode rectifiers is fed with three phase symmetrical voltage supply (120 degrees). The simulation was made independently of the results obtained with JMAG, using PSIM software (and ideal sinusoidal voltage sources), due to the fact that until now a co-simulation between JMAG and PSIM was not successful. The output voltages of the 7 rectifiers are presented in Fig. 9, considering that a lower voltage per phase was needed in order to obtain a rectified voltage of around 450 V. The advantage of this configuration is that the voltage rectified is almost without fluctuations at a given rotor speed (Fig. 10). The disadvantage is that, using 7 rectifiers connected in series, the losses due to diodes forward voltage (voltage drop during diodes conduction) is relatively high, thus the power losses in the rectifier system is increased.

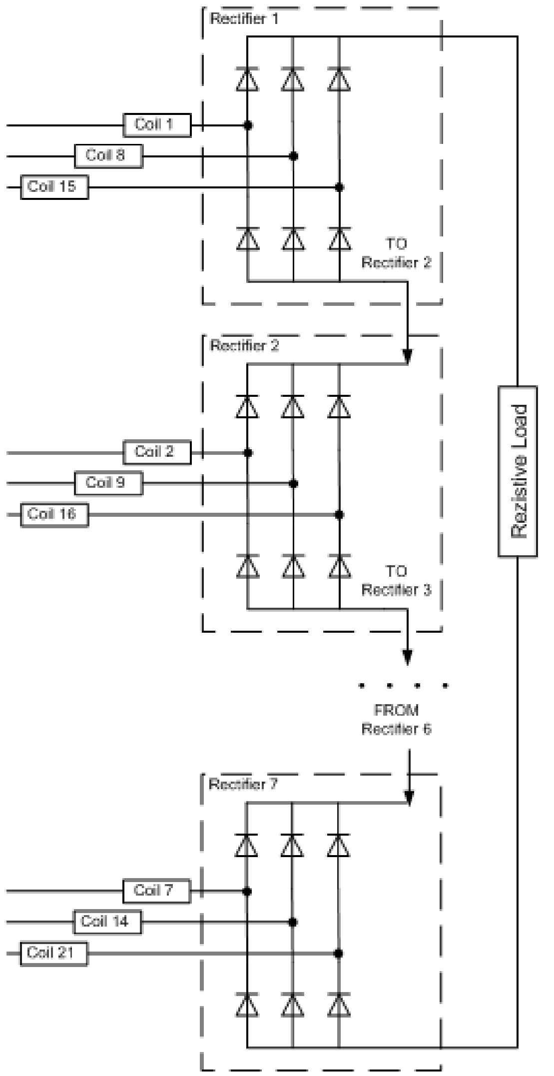

Fig. 8. Electric circuit of the PM generator.

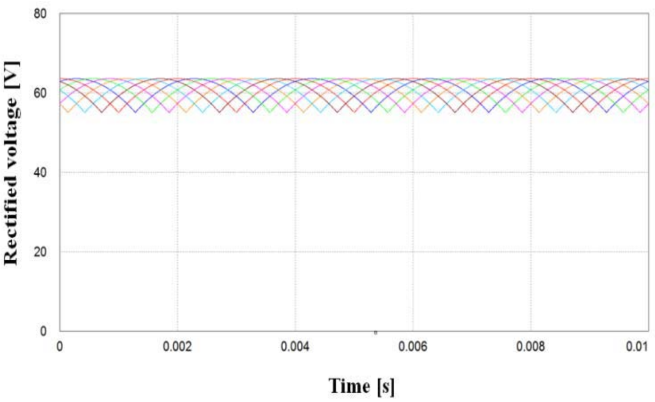

Fig. 9. Rectified voltage measured at the output of each of the 7 rectifiers (PSIM simulation using ideal sinusoidal voltage sources).

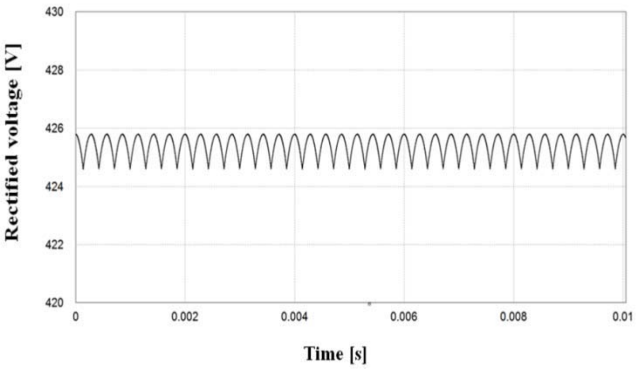

Fig. 10. Rectified voltage measured at the output of the rectifier system (PSIM simulation using ideal sinusoidal voltage sources).

## IV. CONCLUSION

In this paper an analytical electromagnetic design of the RF spoke-type interior-PM small-scale generator has been carried out with the aim of determining the main geometrical dimensions for given specifications. A 2-D and 3-D finite element magnetic field analysis has then been employed to evaluate the electromagnetic design, and to accurately determine the magnetic flux distribution, electromagnetic torque, Joule and iron losses under rated-load conditions.

The FE-computed design-analysis results prove that this generator topology is well suited for low-speed micro-wind power applications and the generated DC voltage is very well filtered, eliminating thus the need to use capacitors connected to the DC bus.

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