Permanent Magnet Generator for Counter-Rotating Vertical Axis Micro-Wind Turbine

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Abstract — **This paper approaches the design using two optimization techniques for a permanent magnet generator used in a micro-wind turbine, with a major importance on the overall performances of the energy conversion system. The proposed micro-wind generator has two armatures and both are rotating in opposite directions.**

Index Terms-- **Direct drive, finite element analysis, genetic optimization algorithm, permanent magnet generator, space mapping optimization technique, wind energy conversion systems.**

I. INTRODUCTION

Economic and environmental issues are the main reasons for developing a clean, efficient, and, last but not least, environmentally friendly power generation systems. This paper approaches the electromagnetic design and finite-element analysis of a radial flux NdFeB permanent magnet machine for use as direct-driven generator for counter-rotating vertical axis micro-wind turbine. A special design of permanent magnet generator (PMG) is developed being characterized by the fact that the machine does not have stationery parts, thus, the two armatures of the PMG (one with permanent magnets and one with coils) will rotate, but in opposite directions.

Recently, the interest regarding the vertical axis wind turbine (VAWT) is increasing [1],[2] and some researchers have carried out studies on lift type VAWT, with advantages based on the wind direction independency, simple design and low costs. Also, VAWT is mostly viable for places with low wind speed regimes where (horizontal axis wind turbine) HAWT could be uneconomical.

The proposed VAWT is composed of two Darrieus wind turbines which are rotating in opposite directions. Therefore, the direct drive generator has to be developed characterized by the fact that its two armatures will be rotating in opposite directions, each connected to one of the Darrieus turbines (Fig. 1 (a)) [3].

Permanent magnet generators (PMG) have been an object of numerous research studies [4], [5] with different structures that can achieve high efficiency due to reduced losses at rotor level, for a wide speed range compared to induction machines. Thus, the PMG has been considered a suitable candidate for the proposed wind energy conversion system applications.
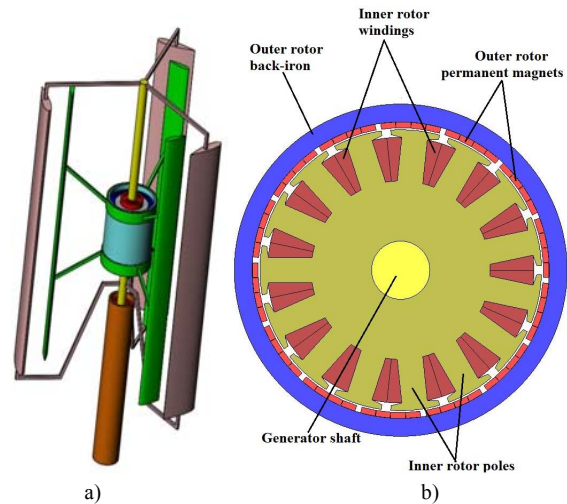

Fig. 1. The experimental model assembly of the VAWT; a) generator with the two Darrieus turbine and b) 2D view of the PM Generator

The choice of poles and phases number must be in accordance with the intended application and required performances. By considering the feasible pole numbers according to the nominal speed of the machine to be designed, the least common multiple between the number of poles and the fundamental winding factor have to be as high as possible. By taking in account these criterions and also the fact that an exterior magnetic rotor confers a larger amount of drive torque than an inner rotor generator with the same diameter, the proposed permanent magnet generator has 14 rotor poles mounted on the outer rotor and, 15 slots on the inner rotor, connected in a three-phase concentrated winding (Fig. 1 (b)).

In this research, numerical and analytical methods for modeling and optimize the design of the PMG are used, each with its advantages and disadvantages. In the first part an optimization methodology that uses a semi-analytical model is preferred for the speed and accuracy to determine the preliminary design of the generator, which underlies the second optimization using Multi-Objective Genetic Algorithms for performing multiple numerical case analyses accompanying optimization calculations for greater accuracy.

II. MODELING OF THE PMG

An analytical simulation model has been considered for characterizing the electromagnetic phenomena of a PMG

which has its basis on the geometrical and electrical circuit equations described in [6], [8], [9], [11]. Being an analytical model it relies only on the amplitude of the involved quantities by computing only peak or mean values, thus obtaining a fast simulation time for it, but causing an inability of some phenomena prediction in the torque, currents or flux waveforms. As several sizing equations rely on some input parameters, which are presumed fixed and not going to be optimized, few assumptions have been made for calculations, among which:

- the slot copper filling coefficient was set to 0.5;
- the induction of the magnets was set to 1.2 [T];
- the number of rotor pole pairs was set to 7;
- the number of stator slots was imposed 15;
- the shape of the magnetic induction in the airgap was considered ideal;
- the saturation effect was not accounted for.

The implementation of the equations was performed in MATLAB environment, without any phase control realization.

Due to the fact that the non-linearity characteristics are not analyzed in this analytical model, a finite element (FE) numerical model has also been realized in order to obtain more precise results. This FE model was created based on the geometrical parameters and the numerical field evaluation was performed in JMAG Designer environment. Several steps were followed for creating the model in JMAG, i.e. the geometry creation, the materials setting, the winding configuration set-up, the conditions setting, the mesh generation, the electrical circuit modeling etc. As this is time consuming and also difficult, a script file based Visual Basic language, which incorporates all of the above, has been set in place for allowing the automatic creation of the FE model in a short period of time. This approach helped to investigate different generator topologies by simply changing the geometrical dimensions. For the FE analysis a full 2D view of the generator was considered (Fig. 1(b)).

III. OUTPUT SPACE MAPPING PROPORTIONAL OPTIMIZATION METHOD

A. Mono-objective function

The objective function proposed is the maximization of the PMG efficiency. This objective function can be rephrased and described as finding the optimum design variables $\hat{x}$ that minimize the distance between the efficiency obtained with the analytical model and a certain reference value $\bar{y}$.

$$\hat{x} = \arg_{x\in\mathbb{R}}\min\|\eta - \bar{y}\|, \text{ with } \bar{y} = 95[\%] \qquad (1)$$

B. Design variables and constraints

The continuous (C.) type design variables considered to be optimized in accordance to the objective function defined above are summarized in Table I, along with their associated boundaries.

TABLE I
DESIGN VARIABLES OF THE PMG WITH OSMP

Design variable	Type	Bounds
Stator bore diameter [mm]	C.	$D_s\epsilon[20\div100]$
Axial length [mm]	C.	$L_a\epsilon[10\div100]$
Air gap thickness [mm]	C.	$g\epsilon[0.5\div1]$
Current density [A/mm²]	C.	$J_c\epsilon[2\div8]$
PM thickness [mm]	C.	$h_{PM}\epsilon[1\div4]$
Magnetic induction in the air-gap [T]	C.	$B_g\epsilon[0.6\div1]$
Magnetic induction in the rotor yoke [T]	C.	$B_{ry}\epsilon[0.6\div1.6]$
Magnetic induction in the stator yoke [T]	C.	$B_{sy}\epsilon[0.6\div1.6]$
Magnetic induction in the stator teeth [T]	C.	$B_{sth}\epsilon[0.6\div1.8]$

Several constraints were also considered to ensure the feasibility of the optimization among which:

1) The interior diameter of the generator: $D_{int}> 15$ [mm]
2) The exterior diameter of the generator: $D_{ext}< 115$ [mm]
3) The maximum windings temperature: $T_{Cu}< 140$ [℃]
4) The demagnetization of the magnets by ensuring they can withstand a current in the windings twice the rated current in the phase [10]: $I_{ph}< I_{max}/2$;

C. Optimization strategy

This paper presents an optimization strategy that searches for the optimal design of a permanent magnet generator and minimizes in the same time the optimization computation time. When using the optimization to determine the parameters of electrical machines, due to the increased number of design variables this task becomes "heavy" and in order to have good results an increased amount of time is needed. Therefore, this study approaches an optimization strategy that minimizes the computational time. This technique was introduced for the first time in 1995 by Bandler [10] and has been defined in the literature as space mapping. More exactly, output space mapping proportional is used in this paper for defining the optimal geometry of a PM generator.

In order for this strategy to work four elements are required:

1) A *coarse model*, which in this case is represented by the analytical model, for which its lack of accuracy is compensated with the benefit of speed. Thus, as it performs the fastest, the optimization is launched.
2) A *fine model*, represented by the finite element model is used as reference, whose keynote is the precision of the results. Based on this fine model the coarse one is corrected.
3) A *mapping function,* that is a mathematical transformation used to refine the fast model based on the accurate one.
4) An *optimization algorithm,* which is used to determine the optimal results from the optimization process.

In order to have an overview of the differences between a classical optimization process and the one using space mapping strategy, the workflow of the two methods are pointed out in Fig. 2.
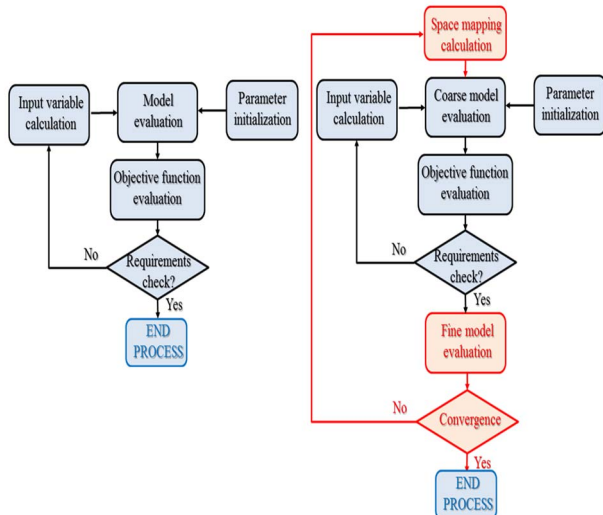
Fig. 2. Space mapping optimization workflow [7].

For this paper, output space mapping proportional (OSMP) is used to correct the outputs of the coarse model (i.e. the analytical model) based on the ones of the fine one (i.e. the finite element model). The OSMP realizes a local correction and the workflow of this technique are represented in Fig. 3.

It is possible to explain Fig. 3 as follows: first the optimization of the coarse model is performed; when this loop is finished the optimal results are used to simulate the fine model. The outputs of the fast and the ones of the accurate model are compared and when the difference between them is smaller than an imposed tolerance the optimization stops and those parameters are considered to be the optimal ones [12], [13].

The general mathematical optimization problem when applying OSMP strategy can be written as in equation.(2).

$$\hat{x}_i = \arg_{X \in \mathbb{R}} \min \| k_{i-1} \text{o} C(x) - \bar{y} \| \qquad (2)$$
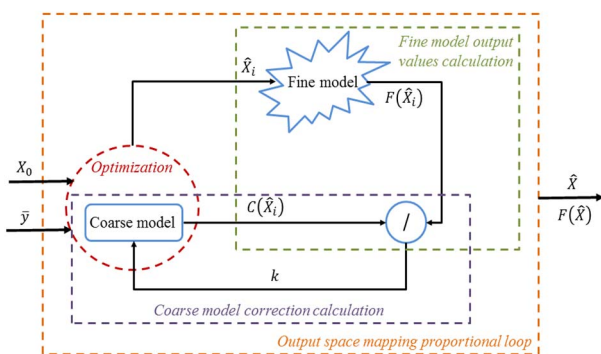

Fig. 3. Interaction between fine and coarse model when using OSMP [15]

where k_{i-1} represents the correction calculated at previous iteration $(i-1)$, $C(x)$ is the coarse model, $\bar{y}$ represents the target to be achieved.

The correction coefficient is calculated as shown in equation (3).

$$k_i = \frac{F(\hat{X}_i)}{C(\hat{X}_i)} = \left(\frac{F_1(\hat{X}_i)}{C_1(\hat{X}_i)}, \frac{F_2(\hat{X}_i)}{C_2(\hat{X}_i)}, \dots, \frac{F_m(\hat{X}_i)}{C_m(\hat{X}_i)} \right) \qquad (3)$$

with $F(\hat{X}_i)$ and $C(\hat{X}_i)$ being the outputs of the fine respectively coarse models at the point $\hat{X}_i$, where $\hat{X}_i$ represents the vector of design variables at the ith iteration.

Using this fast optimization technique it is possible to further proceed with defining a preliminary design of a three phase permanent magnet generator. For this, a link between Matlab environments, in which the analytical model was created and JMAG Designer, used for the finite element model analysis, has been realized. Fig. 4 gives an overview of this link between the two softwares.

The dataflow from Fig. 4 presents the optimization of the analytical model in Matlab using Multistart fmincon algorithm, following that the optimal geometry obtained, to be saved in a text file along with the initialization parameters required by JMAG Designer. This text file is next accessed by the VBScript file in order to build the FE model and to run the transient field analysis of the generator. When the transient simulation is finished the results are saved in an excel file and introduced afterwards in Matlab to be compared with the ones calculated with the analytical model.

In Fig. 5 is presented the convergence of the both models. After six iterations the optimization is able to find the best geometry of the PM generator.

Further on, this geometry is used as a starting point for a new finite element optimization based on genetic algorithms.
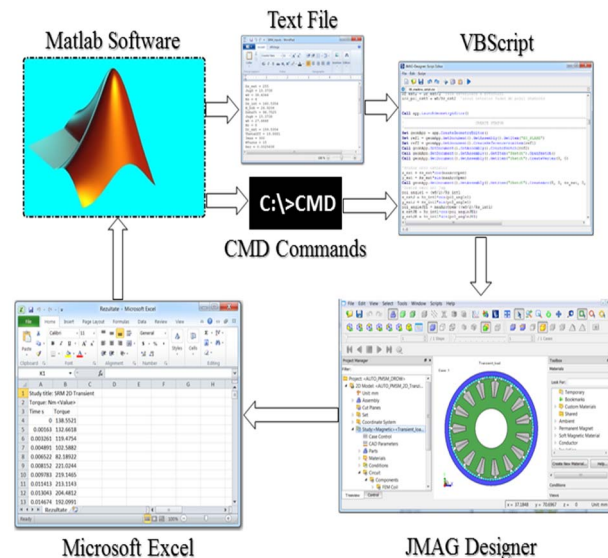

Fig. 4. Structure and data flow of the link between Matlab and JMAG Designer[15].
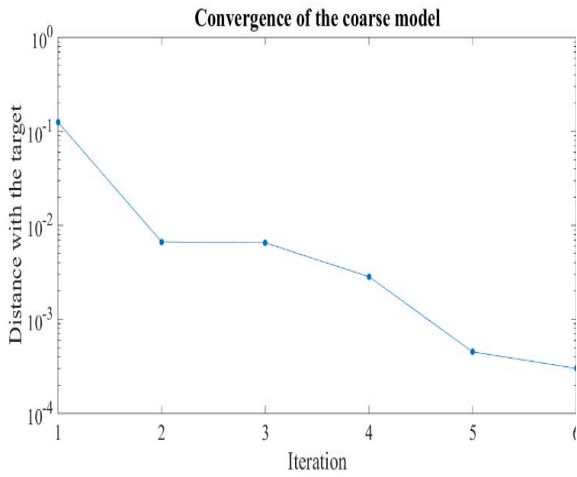
Fig. 5. Fine and coarse model convergence

IV. MULTI-OBJECTIVE GENETIC ALGORITHM METHOD

Based on the mechanisms of natural selection and genetics, genetic algorithms are global search techniques. They can search several possible solutions simultaneously and they do not require any prior knowledge or special properties of the objective function. Moreover, they always produce high quality solutions and, therefore, they are excellent methods for searching optimal solution in a complex problem. This method starts with random generation of initial population which represents possible solutions of the problem. Then the fitness of each individual is evaluated and new populations are generated by genetic operators (Reproduction, Crossover and Mutation) until the maximal number of generation is reached.

In Table II are listed the features obtained with the space mapping technique and constrains of geometrical dimensions for the second optimization process. The intervals of constraints set for the second method are much more restrictive than the first method.

TABLE II
GEOMETRICAL DIMENSIONS OBTAINED AFTER OSMP AND DESIGN
VARIABLES FOR MOGA OPTIMIZATION

Dimension		OSMP design	Min	Max
Outer Rotor	Outside Diameter, [mm]	115	114.3	114.3
	Inside Diameter, [mm]	100.46	96.3	111.3
	Magnet Thickness, [mm]	2	2	3
Inner Rotor	Tooth Width, [mm]	8.9	7	10
	Tooth Fang Width, [mm]	17.78	16	19
	Tooth Tang Thickness, [mm]	2.89	2.2	3.7
	Core Back Width, [mm]	31.18	30	36
	Shaft Diameter, [mm]	20	20	20
Axial length [mm]		12.2	10	15
Air gap thickness [mm]		0.73	0.6	0.8

The optimization process aims to find the best compromise between the efficiency of the generator, the produced electromagnetic torque and to reduce the mass of active materials. The following function was used to accomplish these requirements:

$$f = \frac{P_{out} - Losses}{P_{out}} * 0.5 + \frac{T}{T_i} * 0.25 + \frac{L_{ai}}{L_a} * 0.25 \qquad (4)$$

where, P_{out} represents the output power; Losses designates copper losses and iron losses; T is the average electromagnetic torque, Ti, the initial average electromagnetic torque; L_a and L_{ai} is the axial length during evaluation process, respectively initial axial length of the generator.

In Fig. 6 are presented the values of the optimization function during the optimization process using the Multi-Objective Genetic Algorithm method (MOGA). After completing more than 500 evaluation steps for constant imposed rotational speed, the final optimized model is obtained and presented in Fig. 7. For the computed time, each iteration lasted less than two minutes to finalize.
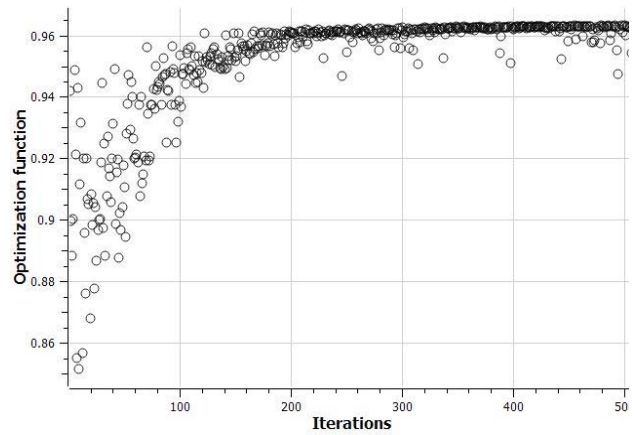

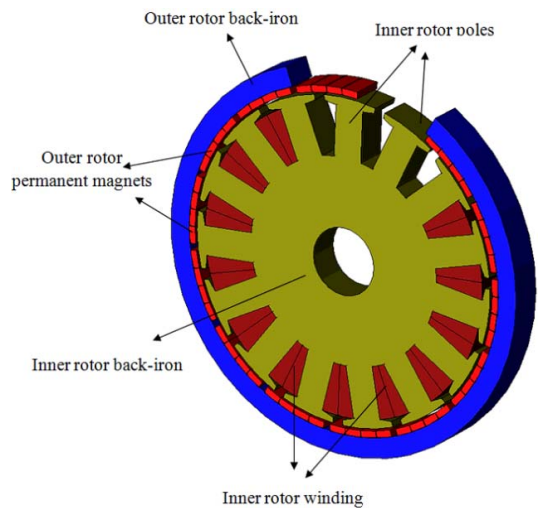Fig. 6. Evolution of optimization function with Multi-Objective Genetic Algorithm method

Fig. 7. 3D view of the PM micro-wind generator after optimization processes

TABLE IV
OPTIMIZED DESIGN CHARACTERISTICS OF THE PM MICRO-WIND
GENERATOR WITH THE TWO MODELS

Parameter		Value	
		OSMP	MOGA
Total weight [kg]		0.806	0.7958
Average output Power [W]		236	259
Power Losses [W]	Copper	14.1	13.1
	Iron	8.27	9.27
	Permanent Magnets	3.4	2.18
Average electromagnetic torque [Nm]		1.67	1.8
Efficiency [%]		89	91.6

A comparison between weight of active materials, power, losses, torque and efficiency of these two models after completing the two optimization process are presented in Table IV. In order to have a fair comparison, the length, outer diameter, number of turns, wire size, the value of isolated resistive load and rotational speed of the generator have been set up to the same values.

In Fig. 8 and Fig 9 are presented the computed three-phase stator-windings sinusoidal voltage and current waveforms in a symmetrical distribution for the model obtained with MOGA method (continuous line) and OSMP method (ellipse marker).

Fig. 10 presents the developed electromagnetic torque of the micro-wind generator. The average value for the electromagnetic torque increases with approximately 7.8%
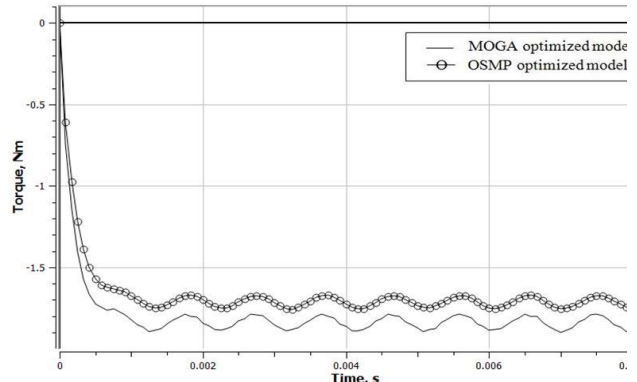

Fig. 10. Dynamic electromagnetic torque of the PM micro-wind generator under resistive load condition.

according to second optimization method. It can be observed that during operation, there are some torque ripples. The cogging torque is below 2% from the rated electromagnetic torque (Fig. 11).

In order to calculate the energy efficiency of the micro-wind generator the loss study has been carried out. The inner rotor iron losses are estimated at a value of 4.8 [W] according to results obtained with first model and a value of 5.2 [W] for the second model. Fig. 12, shows the total Joule losses, that reduced by 3 [W] in the case of final model. These losses are represented by copper losses, outer rotor back-iron losses, and permanent magnet losses.
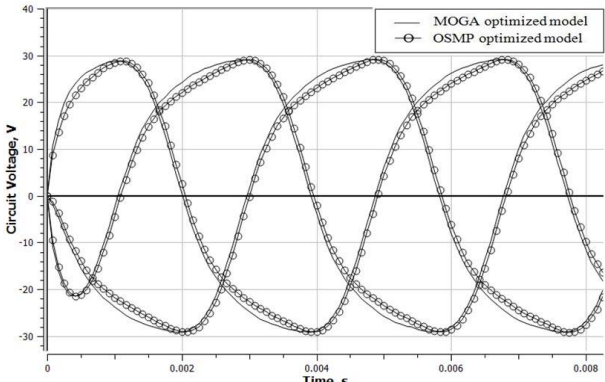

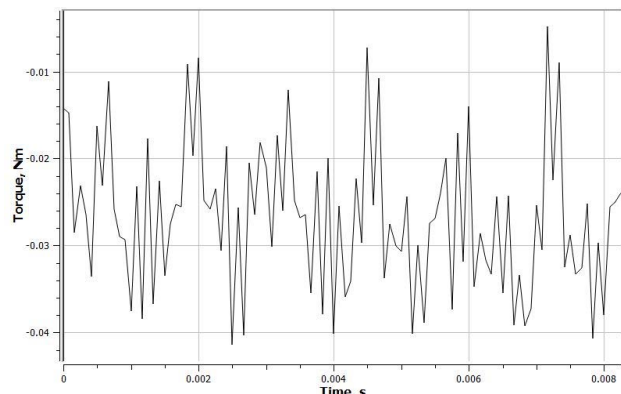Fig. 8. Voltage waveforms in a three-phase symmetric system.
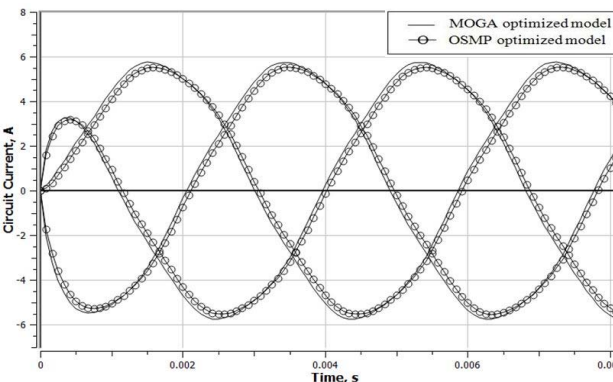

Fig. 11. Cogging torque.

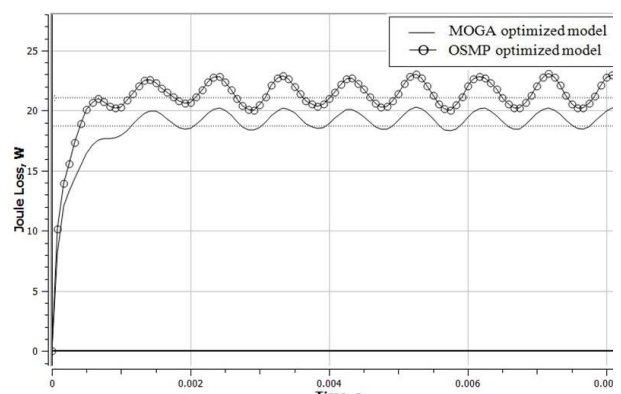Fig. 9. Current waveforms in a three-phase symmetric system.
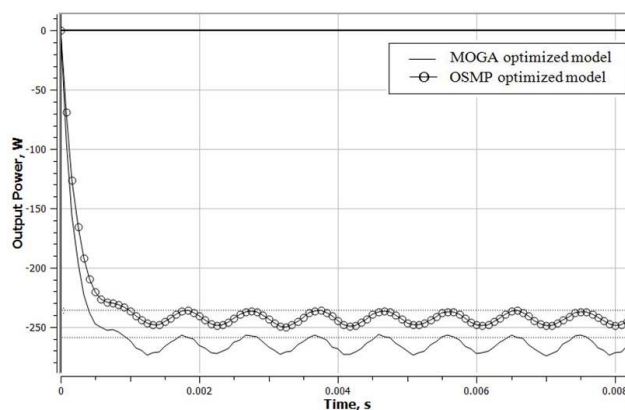

Fig. 12.Total Joule losses after FEM analysis.

Fig. 13.Output powers of the optimized PM micro-wind generator models

In Fig. 13 the output power of the optimized PMGs are given. The results with MOGA model fulfill the main objective of the optimization process, that is to obtain an output power of 250[W] at rated speed of 900 rpm for the outer rotor, respectively 600 rpm for the inner rotor (1500 rpm relative speed).

The rather small difference between the results can be easily observed and proves that the OSMP offers satisfactory results in a short computation time and represents a good starting point for MOGA method. The latter represents a suitable approach in solving the problems encountered in practice having a complex geometry. The advantage of this method is represented by the precision of calculations but the hardware resources used and the high computation time represent the main disadvantage.

CONCLUSION

This paper has presented the design of a PM micro-wind generator for a counter-rotating vertical axis micro-wind turbine. Two optimization methods have been presented with the aim of determining the main geometrical dimensions for given specifications. A 2D finite element analysis has been employed to compare the results obtained in order to evaluate the electromagnetic design accurately, to determine the electromagnetic torque, Joule and iron losses under rated-load conditions of the micro-wind PM generator.

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