

Some Examples that Use the FEM in PM Generators Analysis

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Abstract—The present paper refers to some examples that use the finite element method (FEM) in the process of analysis, design and optimization of the permanent magnet (PM) generators used in wind applications. The 2D-FEM program Opera 13 of Vector Fields is used in the analyzed examples. These examples refer to two types of radial flux low speed PM generators of 5 KW for wind applications. Some possibilities of electrical machine optimization, using the FEM-programming packages available today, are pointed out during the present paper.

Index Terms—PM generator, finite element method, optimization, wind applications.

I. INTRODUCTION

In the last forty years, ongoing and fast developments of numerical techniques for the particular questions concerning electrical machines can be noticed. This development can be seen in parallel with the efforts and success of the software and hardware computer industry in producing powerful tools. Computers as well as commercial software are now ready to be applied to solve realistic numerical models of technical relevance. Of course, there are enough complicated problems and questions, which are not yet answered to a satisfactory extended.

At the time, when not too many computers were available yet, the design of electrical machines was performed in the classical way, by using one-dimensional model (1D). Particular electromagnetic parts of the machine are considered to form a homogenous element in a magnetic circuit approach. In this approach the knowledge of particular “design” factors is assumed. Such models enabled the calculation of specific stationary working point of the machine. Laplace transformations applied to such models made it possible to analyze the machine for dynamic operations. The refinements of 1D models yield the technique of magnetic equivalent circuit models.

A very rough figure can be drawn in saying that the development of numerical methods for electrical machines started with the finite difference method (FDM) which quickly was followed and further overtaken from the finite element method (FEM).

With the first numerical models of electrical machines, in the 70s, electromagnetic fields considering imposed current sources could be simulated by applying first order triangular elements. Further developments of the finite element method lead via the definition of external circuits to problem formulations with imposed voltage sources, which were more accurate models with respect to the realistic machine that is operated by a voltage. Today’s developments are directed to all aspects of coupled fields. There are the thermal/magnetic problems or structure dynamic field problems coupled to the electromagnetic field.

Parallel with the developments of the finite element method first attempts to numerically optimize the finite element models were made. Optimizations of realistic machine models were first performed in the late 80s and early 90s.

However, research directed to accelerate the numerical solver is going on as well. Extension of the overall machine models can be made by applying more realistic material models. Hysteresis effects and material anisotropy are still a lack in many software packages. Special winding models allow reducing the size of a numerical model significantly and therefore the computation time as well. To avoid long lasting transient simulations single-phase machines can be modeled by a time-harmonic approach by modeling separate rotor models for the rotary fields in reverse respectively rotation direction of the rotor.

However, with the developments of numerical techniques around the electrical machine analysis, it must be noticed that the classical approach cannot be replaced by the numerical models. Enormous expertise and knowledge to model the various electromagnetic effects appropriate and accurately are still required. The modeling/solving/post-processing of numerical motor models still requires substantial engineering time and cannot replace the quick and correct answer of an exercised motor design engineer. Both experts, probably in one person, numerical modeling and electromagnetic motor design engineer, are required for successful and novel developments in the engineering discipline.

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II. FEM ANALYSIS OF PM ELECTRICAL MACHINES

In general, a power system consists of a mechanical turbine, an electrical generator and control block. Because of the mechanical constrains, in most of the cases the rotational speed of turbines is low. Usual generators however have high nominal rotational speed (1000 rpm or higher) incompatible with the turbine's rotational speed. One of the solutions is to introduce a gearbox between the turbine and the electrical generator, with all the drawbacks of such a mechanical device. An alternative is to have the electrical generator directly coupled with the shaft of the turbine. In this case, the design of the generator must solve the problem of good performances of electrical machines at low values of rotational speed imposed by the primary source of the energy mover. Nowadays there is a trend to use electrical generators directly coupled to the wind turbine, due to the advantages in comparison with the high speed generators coupled to the turbine through mechanical gearbox.

The direct drive PM generators are preferred in the water and wind low speed turbines. They have some advantages like: no gear-box between mechanical turbine and the generator (no losses, no maintenance, no gear noise, etc.); are more efficient, more compact, than other generators; cheaper than the direct drive synchronous generator with electrical winding excitation; smaller dimensions than those of the normal speed asynchronous generator with gear-box, or of the multi-pole asynchronous generator.

The paper analysis numerically some aspects concerning two radial flux low speed PM generators of 5KW for wind applications. After the preliminary classical design of the generators, a numerical analysis using the Opera 2D of Vector Fields has been performed. The classical design process generates the geometrical quantities, the shape and the geometrical dimension of the slot, the air gap form, the number of turns in the coils, the permanent magnets pattern, etc. Using the numerical analysis by FEM programs during the design process, we can analyze and improve the performances of the PM generators. In most of cases it represents a great advantage because the project could be changed during the design process and even some performances of the generator could be optimized.

The cross-section models of the two radial flux low speed PM generators that have been simulated using the Opera 2D-FEM program of the Vector Fields, are presented in Fig. 1. The purpose was to obtain PM generators with a simple structure, good performances and very low cogging torque. The inner rotor has 32 permanent magnets (16 magnetic pair of poles) of alternatively opposite radial magnetization. The permanent magnets used are NdFeB, N35SH. Two types of stators have been used in the design process: one with 33 stator slots (Fig. 1a) and the other one with 63 stator slots (Fig. 1b).

Considering some quantities of high importance in the design process (such as the cogging torque or the back EMF waveform shape), some analysis of these quantities has been

made, performing some optimizations in the geometrical design of the generators.

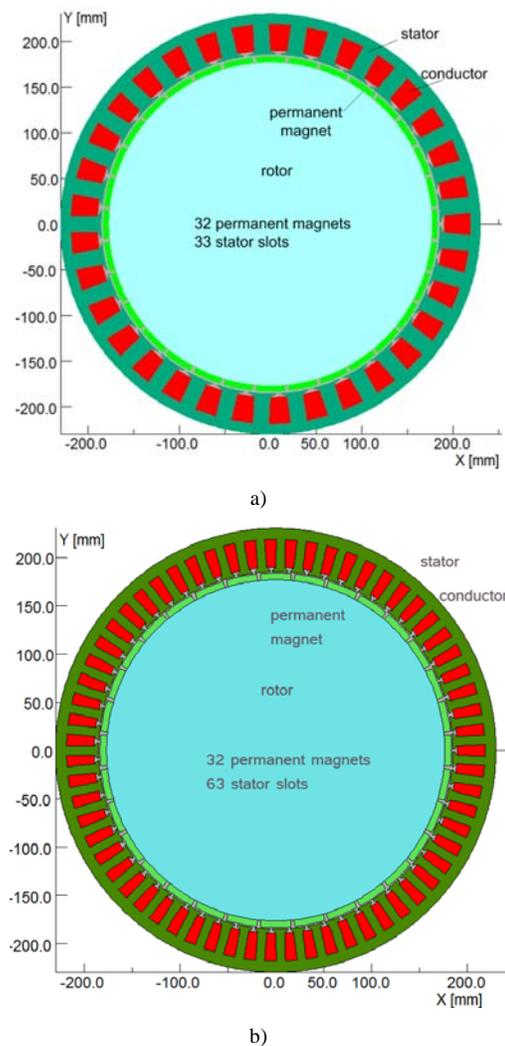


Fig. 1. The numerical models for FEM simulation.

III. MAGNETIC FIELD AND BACK EMF ANALYSIS

Due to the plan-parallel symmetry of the most electrical machines, a cross section of the machine is used for the numerical analyses that involve 2D-FEM programs.

The solution of the magnetic field generated by the FEM program allows to be analyzed some aspects concerning with the design process respectively the functioning of the electric machine, such as: identification of the possible saturated ferromagnetic area for which a reconsidered design process is necessary; the calculus of the iron losses in the main magnetic circuit or in different adjacent regions.

In order to have information about the magnetic field generated by the permanent magnets, a static analysis has been performed. Fig. 2 refers to the magnetic field generated by the permanent magnets of the generator with 33 stator poles. The field lines distribution are sketched in Fig. 2a while the Fig. 2b draw the radial component of the magnetic flux density versus the mechanical angle in the machine air-gap.

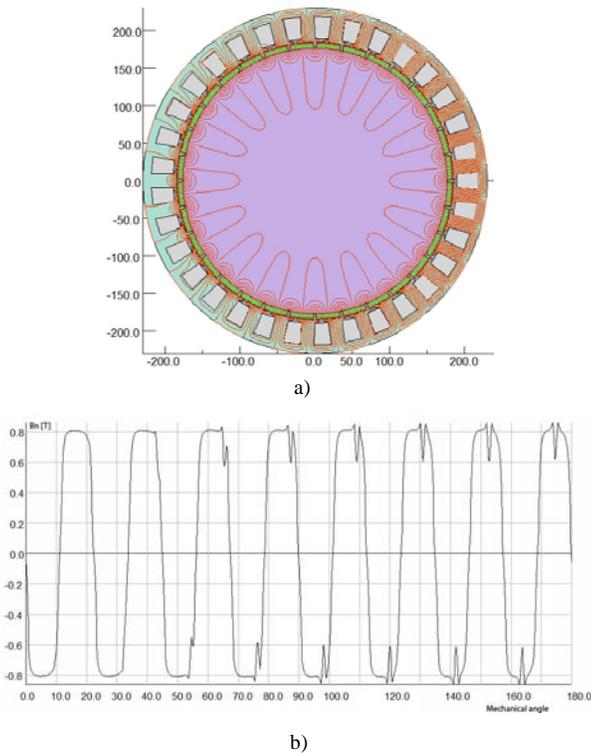


Fig. 2. The magnetic field for the generator with 33 stator slots a) field lines distributions; b) the radial component of the flux density in the air gap.

The same quantities are representing in Fig. 3 for the generator with 63 stator slots.

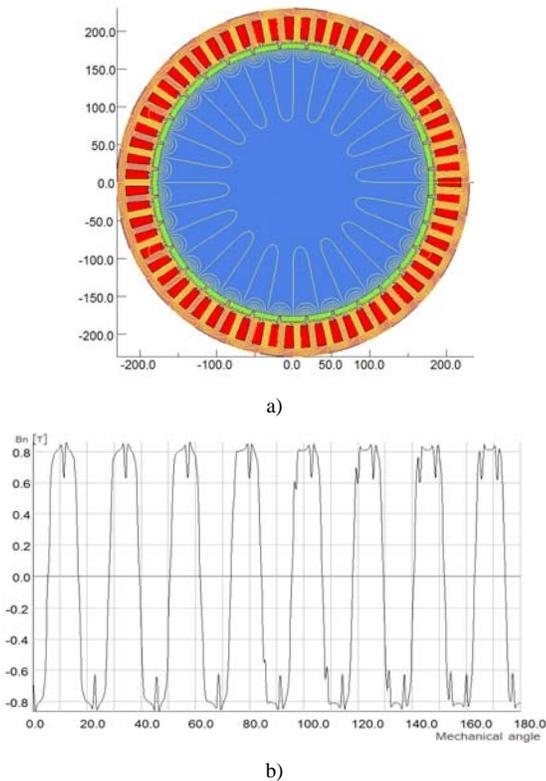


Fig. 3. The magnetic field for the generator with 63 stator slots a) field lines distributions; b) the radial component of the flux density in the air gap.

The dynamic analysis using FEM has been applied to draw the voltage shape of back EMF induced in stator windings. This analysis can take into account the non-linear characteristics of iron cores (the saturation effects), the opening of the stator slots, and the load current effects. Finally, the voltage shape, with Fourier series expansion can be analyzed. In this way, some parts of the generator could be optimized so as to achieve an acceptable waveform.

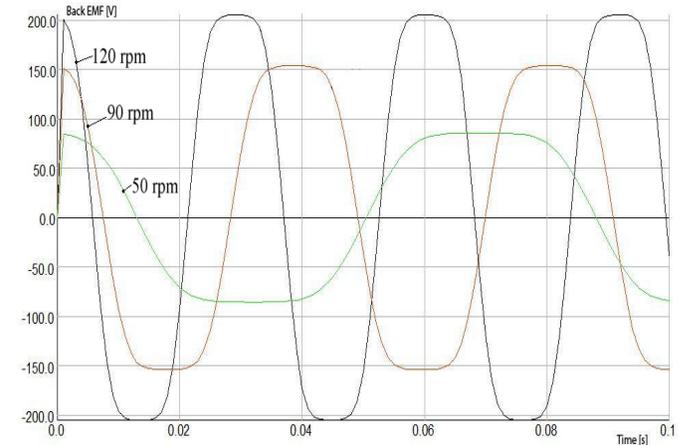


Fig. 4. The dependence back EMF versus time for different rotor speeds of the PM generator with 33 stator slots.

The back emf voltage shape for the generator with 33 stator slots is drawn in Fig. 4, for three different rotor speeds: 120 rpm (the rated speed), 90 rpm and 50 rpm. As we may expect, the magnitude and the frequency of the back emf are depending on the rotor speed. The numerical simulated shapes prove a frequency of $f=32$ Hz for a 120 rpm speed, $f=24$ Hz for 90 rpm and $f=13.33$ Hz for 50 rpm. The FFT analysis of the voltage waveform, point out the large value of the third harmonic.

The back emf voltage shape for the generator with 63 stator slots, using the same rotor speeds, is drawn in Fig. 5.

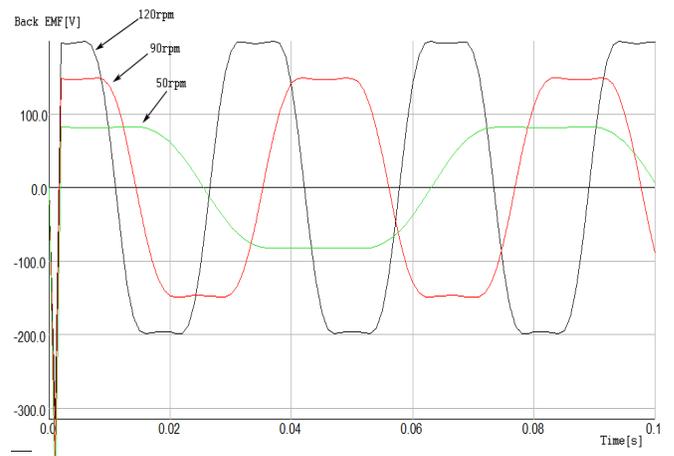


Fig. 5. The dependence back EMF versus time for different rotor speeds of the PM generator with 63 stator slots.

The influence of the pole coverage ratio over the back emf

waveform for the generator with 33 stator slots is presented in Fig. 6. There has been analyzed the back emf waveform for four different widths of magnets. This type of analyze allows an optimal value of the magnet width to be set so as to achieve the desired form of the back emf waveform.

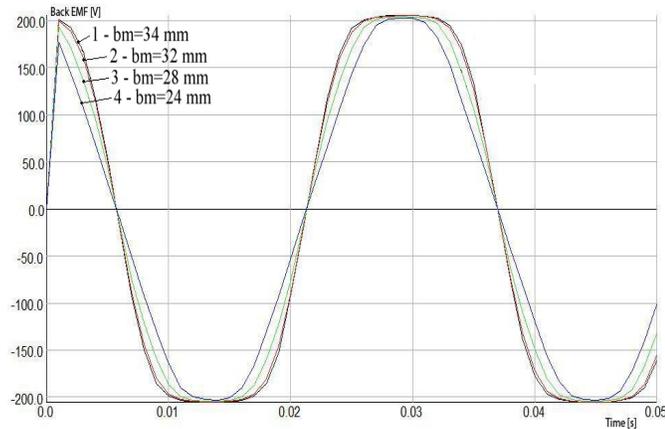


Fig. 6. The dependence back EMF versus time for different magnet widths of the PM generator with 33 stator slots.

IV. COGGING TORQUE ANALYSIS

Cogging torque is one of the most important quantities that have to be controlled during the design process of the PM generators. Due to the magnetic field generated by the permanent magnets, on the rotor acts a torque (cogging torque) even without current flows in the stator coils. The cogging torque depends on the ratio between the number of the statoric slots and the poles, the generator geometry and also on the pole coverage of the magnets. Large values of the cogging torque are unacceptable in the generator behavior. From this reason, the value of the cogging torque should be reduced during the design process of the generator by using the FEM analysis.

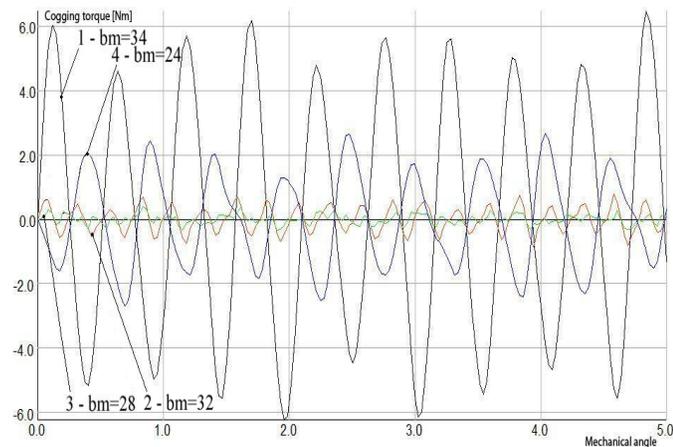


Fig. 7. The dependence cogging torque versus mechanical angle for different magnets widths of the PM generator with 33 stator slots.

The two types of generators have been designed with such a ratio between the number of the statoric slots and the magnetic

poles to generate a low cogging torque.

The dependence cogging torque versus rotor position (mechanical angle) for the generator with 33 stator slots has been drawn in Fig. 7 for different magnet widths. Due to a favorable rate between the number of the stator slots (33 slots) and the number of the rotor poles (32 permanent magnets), the generator has been design with a very low cogging torque. Even for wide values of the magnetic width, the cogging torque is less than one percent of the rated torque of the generator.

Similarly for the generator with 63 stator slots, the dependence cogging torque versus mechanical angle drawn in Fig. 8 shows low values comparing with the rated torque of the generator.

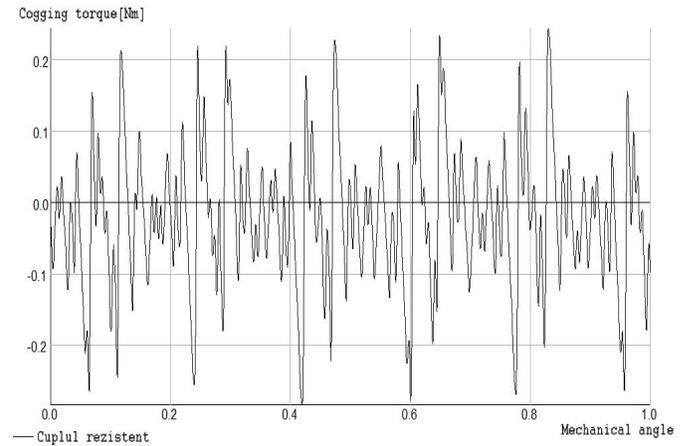


Fig. 8. The dependence cogging torque versus mechanical angle for the PM generator with 63 stator slots.

The optimization of the number of the stator slots or the number of the rotor poles, or the ratio between the two values can be done by performing a numerical analysis using a FEM program. The minimization of the cogging torque values performed by FEM analysis generates optimal dimensions in the design process of the generator.

V. CONCLUSIONS

The present paper emphasizes the great advantage of the FEM analysis used during the design process of the electrical machines, in particular PM generators. Using the numerical analysis of the PM generators during the design process avoids some errors that could be encountered and allows optimizing some performances of the machine by some corrections of the design. Such adjustments during the design process could have considerable economical benefits.

The prototype of the radial flux low speed PM generators with 33 stator slot has been realized following the classical design combined with the numerical analysis using FEM program, Fig. 9.



Fig. 9. Photo of the 5 KW PM generator.

The specification and main dimensions of the three-phase generator are presented in Table I.

The prototype was tested and analyzed on no-load and load conditions.

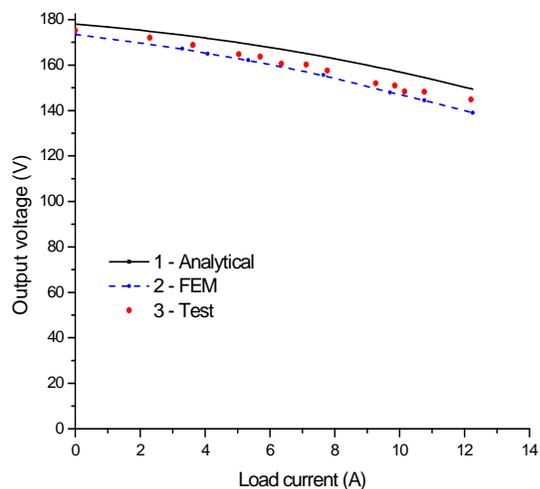


Fig. 10. The measured and estimated output voltage as function of load current for the PM generator with 33 stator slots; 1-analytical method; 2-FEM analysis; 3-measured values.

TABLE I.
SPECIFICATIONS AND DIMENSIONS OF THE GENERATOR

Rated output power (W)	5000
Rated rotational speed (rpm)	120
Rated output phase voltage (V)	145
Number of poles	32
Number of stator slots	33
Inner stator diameter (mm)	370
Stator winding factor ξ_1	0,954
Air-gap (mm)	1,4
Length of stator core (mm)	120
Magnet radial thickness (mm)	7
Magnet width (mm)	32
The stator winding resistance R (Ω)	0,98
The magnetizing reactance X_m (Ω)	1,05
The leakage reactance X_σ (Ω)	4,7
Permanent magnet NdFeB	N35SH

In Fig. 10 is presented the variation of output voltage estimated during the design process, curve 1. The curve 2 is obtained using the FEM. The measured values of the output voltage at resistive load are marked on the figure with few points. As a conclusion, there are good agreements between the analytical results, FEM results and the measured values.

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