FEM-based Analysis of a Hybrid Synchronous Generator with Skewed Stator Slots

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***Abstract*—The paper presents a simulation study of a hybrid synchronous generator (dual excitation system - permanent magnets and electromagnets) with skewed stator slots. The main goal is to establish if the skewing of the slots brings a significant improvement of the air-gap flux density and of the induced stator voltage. The skewness angle is the parameter in discussion. The study is based on finite element method analysis. Due to the particular geometry of the stator slots, a multilayer approach is employed.**

***Index Terms*—finite element method, hybrid synchronous generator, multilayer analysis, skewed stator slots.**

I. Introduction

Concepts like “green energy” or “zero emissions” became lately the new religion in the modern technology development. Mainly generation but also utilization of the energy must accomplish unpolluted-environment constraints. From this point of view, wind energy conversion or “clean” transport by road takes the top of the table in the attention of the specialists. To meet the new requirements, both of them need new electric machines with high performance. In this respect, the motors with permanent magnets (PMs) get a special attention since they provide high efficiency (absent losses of the electromagnetic excitation system), superior power density and power factor. [1]-[19]. Obviously, the most important drawback of the PM machines consists in the constant excitation field. For this reason hybrid topologies have been developed provided with both PMs and electromagnetic excitation systems. A second inconvenience of the PM machines consists in the shape of the air-gap flux density curve. Usually, the presence of magnet segments (surface mounted, inset or buried) gives a more or less trapezoidal wave with the unavoidable consequences of the high order harmonics. Therefore, efforts in obtaining a sinusoidal shape should be carried out. To this effect, we present in this paper an analysis based on finite element method that simulate a hybrid synchronous machine with skewed stator slots. The study takes into discussion both 2D and multilayer transient analyses.

II. Machine Topology

The machine presented in this paper is practically made of two separate units placed on the same shaft. They are axially separated by a small air gap of a few millimetres, Fig. 1. The stator cores of the two semi-machines are identical and each of them has 36 slots.

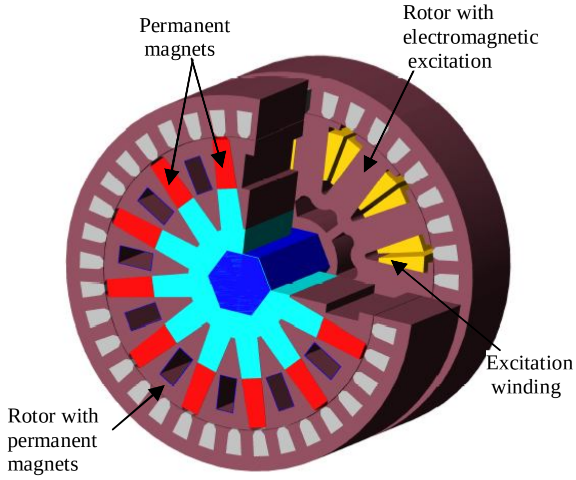


Figure 1. Hybrid synchronous generator topology

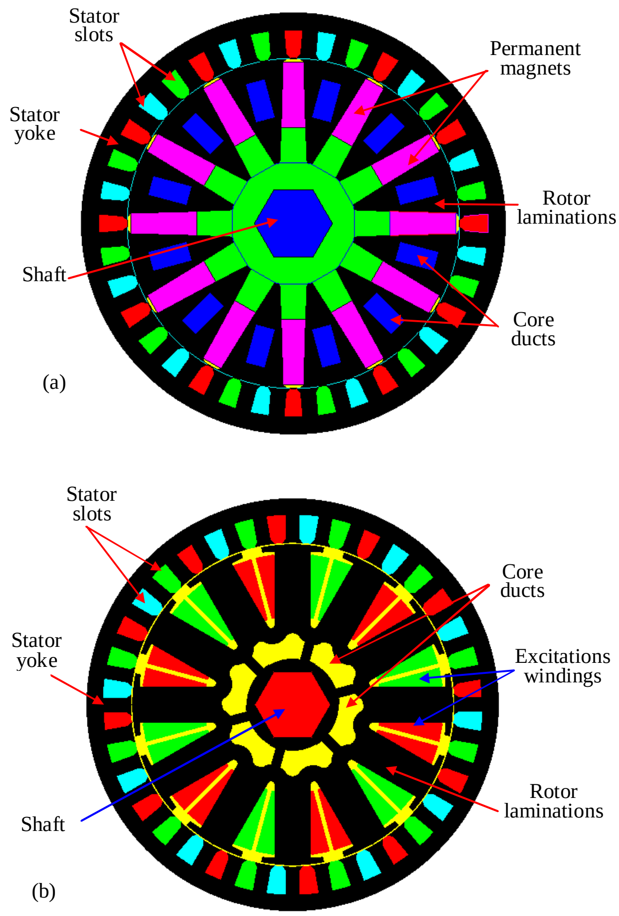


Figure 2. Cross-section of the two rotors

Digital Object Identifier 10.4316/AECE.2011.04002

The rotors of the two units are different. One of them has 12 inset permanent magnets, Fig. 2a, and the other has 12 electromagnetic poles, Fig. 2b. The common element of the two semi-machines is the stator winding where the voltages induced by the two excitation systems are totalled. This apparently complicated solution has the following reason. When the machine operates under generating duty, the amplitude of the output voltage can be regulated by means of the electromagnetic excitation both in an increasing and a decreasing (negative excitation) way. Under motoring operation, the electromagnetic excitation allows a regulation of the speed and developed torque. The axial length of each semi-machine is also different – 45mm for PM unit and 35mm for the EM unit. As concerns the stator winding, it is a double layer half-coil wave type with 2 turns per coil and 8 conductors parallel-connected.

III. FEM Approach

In order to simulate the behaviour of the hybrid machine under generating duty, the Flux 2D and Flux Skewed packages have been used. This software is based on a numerical computation that uses the finite element method. Flux2D is used for simulating models that have axial symmetry, while Flux Skewed is dedicated to the analysis of the structures with skewed slots (these surfaces and geometric volumes cannot be generated in a 3D representation). This last analysis is practically a multilayer 2D study, which is run by the software package in a single solve stage. Practically, the user decide a number of layers along the axial length of the object (in our case electric machine) and the results obtained for each layer can be subsequently summated. If the electromagnetic phenomena take place in the linear sector of the magnetic characteristic then an arithmetic mean is allowed to obtain the final and global result.

Of great importance for the quality of the results is the density of elements inside the global mesh. In order to reduce the computation time, there must be taken into account the generating of a minimum number of elements, but which should contain a satisfactory density for obtaining reliable results. The computation time rises with an increasing number of elements, but the results are more accurate. Fig. 3 presents the mesh of the two semi-machines.

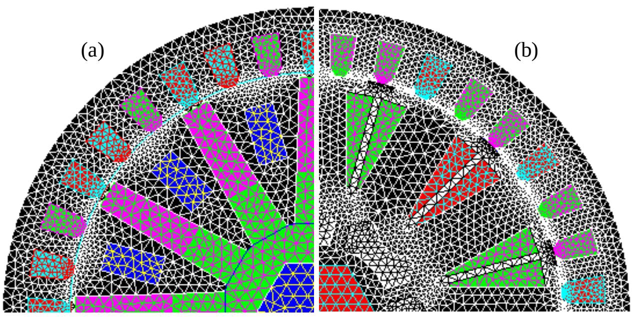


Figure 3. Mesh: a - permanent magnets excitation rotor; b - electromagnetic excitation rotor

Fig. 4 and Fig. 5 present the equivalent electric circuits of the two semi-machines. The circuits simulate the operation of the machine as generator and contain beside the circuit elements that characterize the stator and rotor windings, a rectifier bridge and a load resistance. There are also a few resistances, of high values, destined to simulate voltmeters.

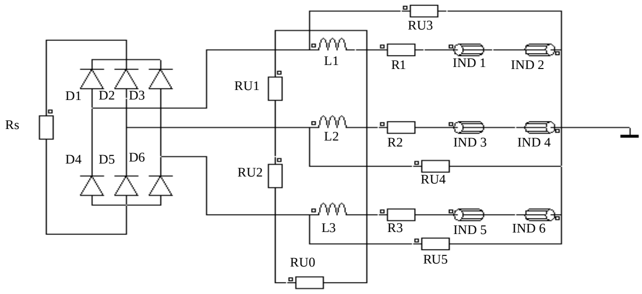


Figure 4. Equivalent circuit – permanent magnet semi-machine

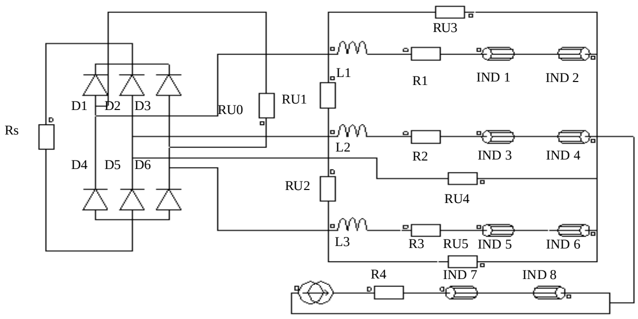


Figure 5. Equivalent circuit – electromagnetic excitation semi-machine

Table I shows the actual values calculated for the hybrid synchronous machine.

TABLE I. NUMERICAL VALUES OF THE CIRCUIT ELEMENTS

Circuit element	**P.M. semi-machine**	**E.E. semi-machine**
Stator winding		
Coil number per phase	12	12
Slot resistance (IND1...IND6)	0,0022 Ω	0,0017 Ω
End winding resistance (R1...R3)	0,0056 Ω	0,0066 Ω
End winding inductance (L1...L3)	0,064 mH	0,068 mH
Rotor winding		
Coil number of turns	-	480
Slot resistance(IND7...IND8)	-	0,36 Ω
End winding resistance (R4)	-	0,38 Ω
Excitation current (I_e)	-	0...±8A
Additional circuit elements		
Load resistance (R_S)	0...10^6 Ω	0...10^6 Ω
Resistance for measuring the phase and line voltages (RU0...RU5)	10^6 Ω	10^6 Ω
Equivalent diode resistance conduction / lock status	0,1/10^6 Ω	0,1/10^6 Ω

The pre-processing stage has been accomplished by defining the permanent magnets. The machine has been provided with Ferrite type magnets having a remnant flux density, Br=0,41T, and a coercitive field strength, Hc=190kA/m.

IV. Results Analysis

A preliminary evaluation of the hybrid machine involved a 2D simulation under transient at constant speed operation analysis. The study takes into consideration separately each semi-machine. Fig. 6 shows the flux lines distribution with the spectre of the 12 poles.

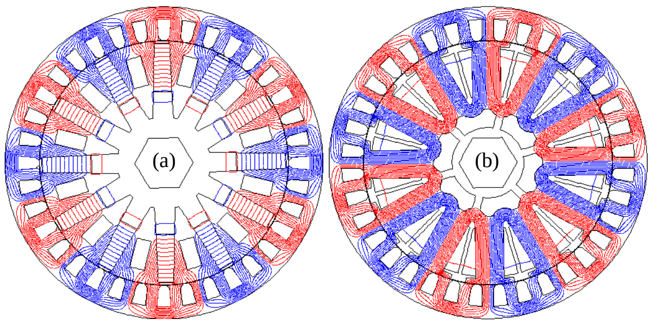


Figure 6. Flux lines distribution: a. PM rotor; b. EM excitation

It is necessary to mention here the vital importance of the rectangular ducts from the rotor core of the PMs semi-machine. They impose certain paths for the flux lines in order to obtain a proper distribution of the air-gap magnetic field. Fig. 8 confirms more clearly this statement. The air-gap magnetic field has a classic trapezoidal shape (excluding the drops cased by stator slots).

Fig. 7 presents the flux density colour maps. One can see that the semi-machine with permanent magnets has a lower magnetic loading of the circuit (right side view) mainly in the rotor. This situation arises from the type of permanent magnets used as excitation system. They have a rather low remnant flux density and consequently both the values inside magnetic core and along the air-gap are rather small.

This apparent drawback is balanced out by the possibility of having a thinner stator yoke.

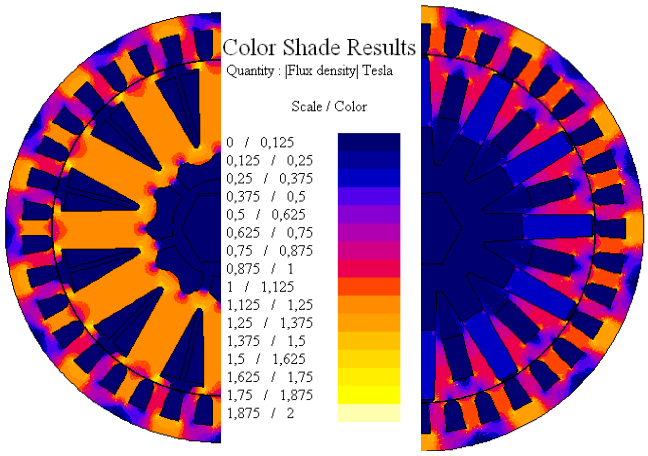


Figure 7. Flux density color map

There is a much important saturation of the magnetic core of the electro-magnetic excitation semi-machine, which corresponds to an excitation current of Iex=4A. Obviously, the degree saturation depends on the excitation current value.

Of high importance in performance evaluation is the air-gap flux density wave. Since the shape is not sinusoidal, a Fourier series analysis is mandatory. As Fig. 8 and Fig. 9 show, both semi-machines have significant high order harmonics and the 3rd, the 5th and the 7th are the most harmful of them. As regards the fundamental, a value of 0.7T is quite acceptable.

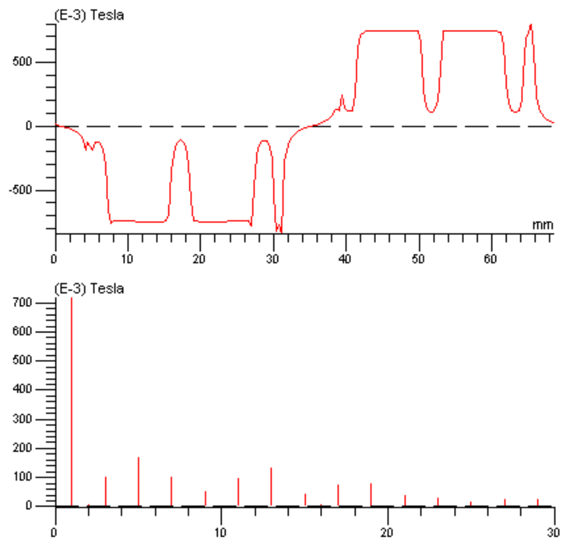


Figure 8. Air-gap flux density and content in high order harmonics - PM semi-machine

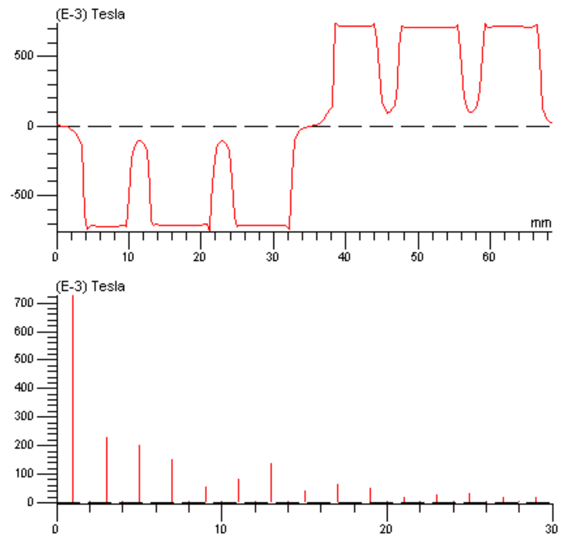
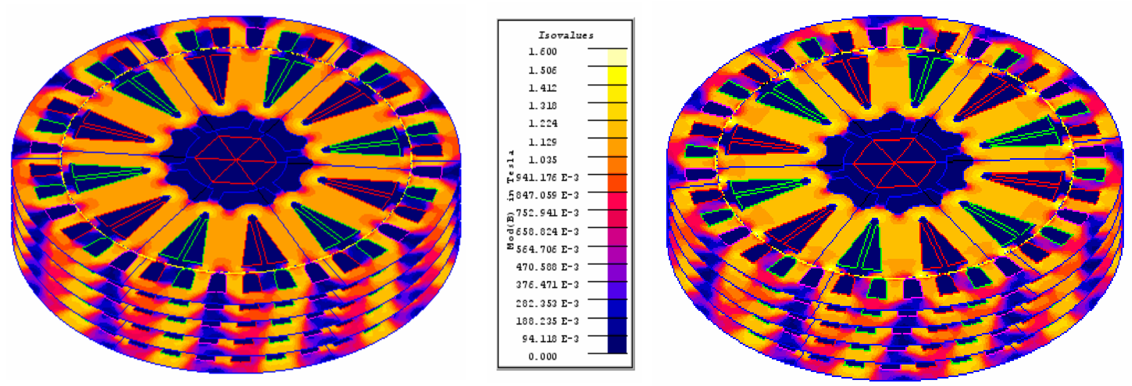


Figure 9. Air-gap flux density and content in high order harmonics - EM semi-machine

The improvement of the air-gap flux density shape and, what is more important, of the induced voltage can be obtained by skewing the stator slots (usually this procedure is applied to rotor slots but in this case is not possible due to permanent magnets).

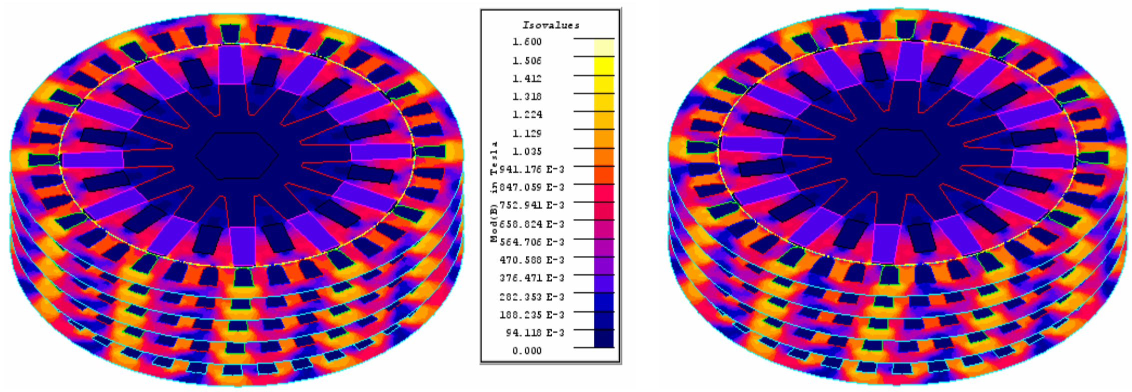
It is well known that the skew degree corresponds to a dental pitch of the opposite winding but again, in this case the PMs semi-machine has no rotor slots. As consequence, taking into consideration the rotor topology of the EM excitation semi-machine, we took into discussion two skewness levels, of 4 and 8 degrees respectively. As we mentioned above, the geometric complexity of the structure allows a FEM analysis only with FluxSkewed package. For our situation, we considered five layers, which are equidistant placed along axial length.

Fig. 10 and Fig. 11 show the multilayer structure, corresponding to the two skewness levels together with the flux density colour maps. Fig. 12 and Fig. 14 present the variation of line voltage, individually considered for each semi-machine.



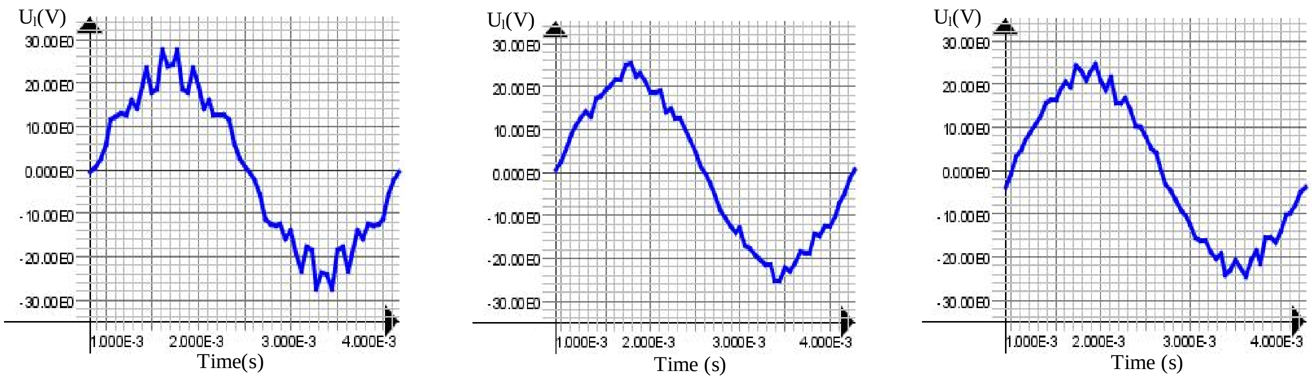
4 degrees skewness 8 degrees skewness

Figure 10. Flux density color map - semi-machine with electromagnetic excitation



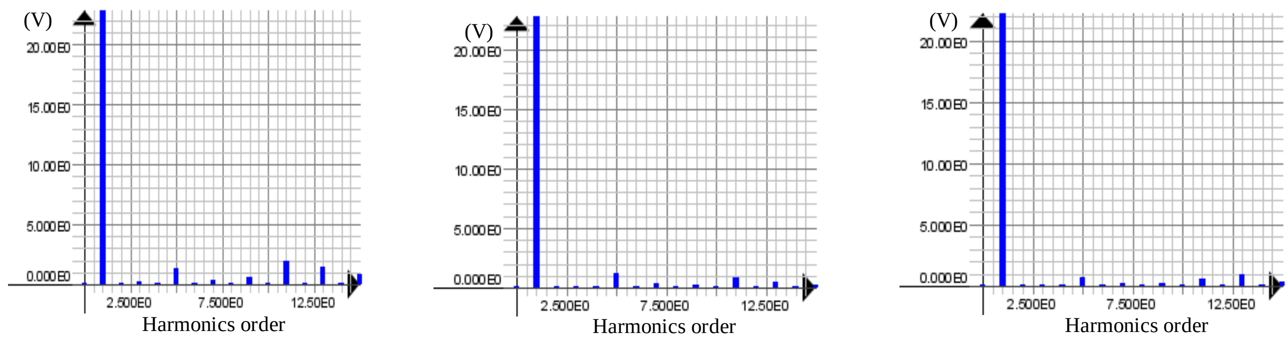
4 degrees skewness 8 degrees skewness

Figure 11. Flux density color map - semi-machine with permanent magnets



straight slots 4 degrees skewness 8 degrees skewness

Figure 12. Line voltage - electromagnetic excitation semi-machine with 4A excitation current



straight slots 4 degrees skewness 8 degrees skewness

Figure 13. Harmonics components of the line voltage - electromagnetic excitation semi-machine

It is obvious that for each structure, the skewness of the stator slots brings a significant improvement of the voltage shape towards a closer to a sinusoidal shape. This statement is attested by the Fourier analysis (Fig. 13 and Fig. 15). Practically, an 8 degrees skewness annihilate the high order harmonics of the voltage.

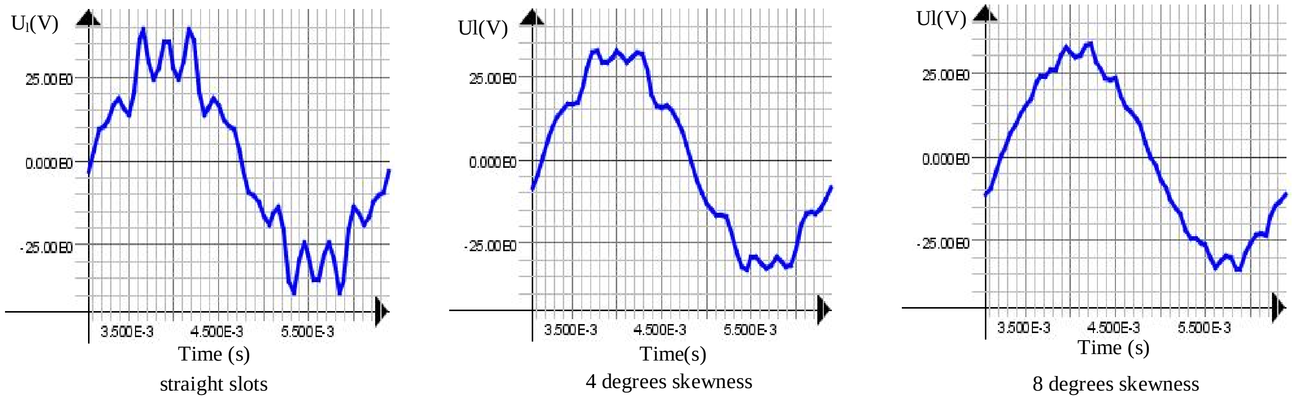


Figure 14. Line voltage - permanent magnet semi-machine

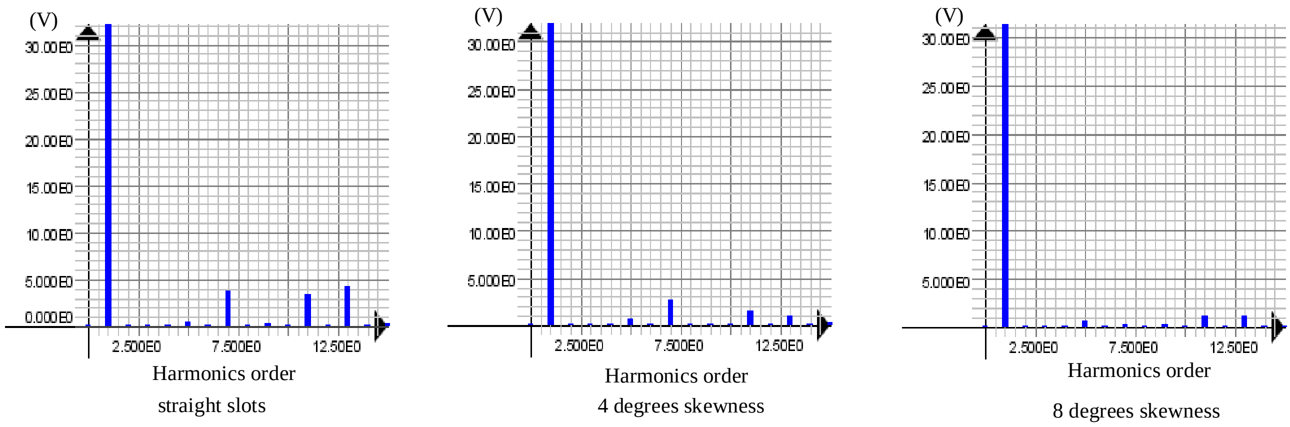


Figure 15. Harmonics components of the line voltage - permanent magnet semi-machine

The resultant voltage produced by the both semi-machines in the common stator winding can be obtained by superposing the individual voltages. Fig. 16 (straight slots) and Fig. 17 (8 degrees skewness) presents in a comparative manner the voltage variation together with the Fourier series analysis. It is again obvious the annihilation of the high order harmonics but just an insignificant decrease of the amplitude of the fundamental.

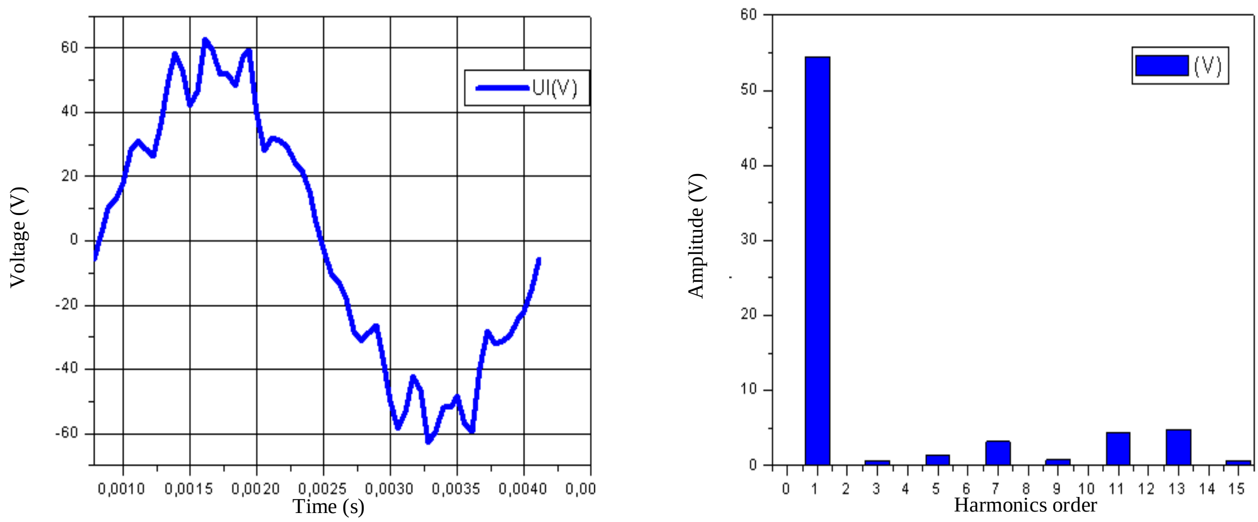
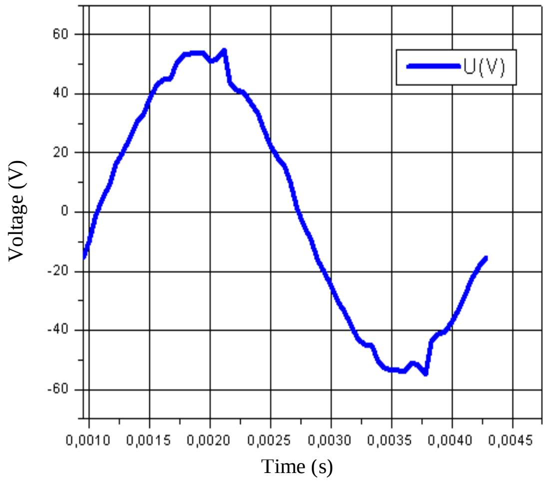


Figure 16. Resultant line voltage and high order harmonics – straight slots



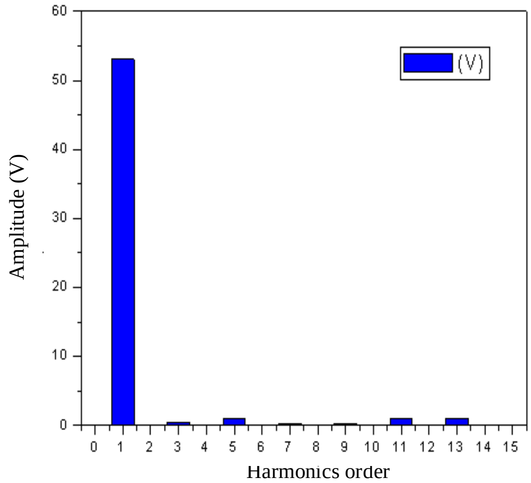


Figure 17. Resultant line voltage and high order harmonics – 8 degrees skewed slots

V. CONCLUSION

The skewed stator slots represent a feasible solution for the improvement of the output voltage delivered by a permanent magnet synchronous machine. The line voltage wave form becomes quasi sinusoidal and an elimination of the high order harmonics is obtained. The skewness of the slots has to be properly chosen in accordance with the structure of the rotor. For this purpose the FEM-based analysis is a convenient and trustful tool.

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