STUDY ON THE CHARACTERISTICS OF A NEW HYBRID SYNCHRONOUS GENERATOR

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This paper presents a study of the behaviour of a hybrid synchronous generator destined to operate on large limits of speed such as generation of electric energy on the basis of wind power or operation on automotives. Mainly the output characteristics are taken into discussion. The study involves both a FEM analysis and experimental tests and comes to a conclusion regarding the opportunity of using this type of machine.

1. INTRODUCTION

Because of the increasing number of the electrical energy users installed in places where the centralised energy distribution system is not available or on the automotives, the studies for increasing the performances of the classic generators that are presently used [1], has been intensified lately. The use of additional permanent magnets between the claw-poles is one of the practical solutions [2]. These studies showed the possibility of increasing the generated power with 20%, especially at low speed, depending on the permanent magnet type, its geometry and position [3]. The disadvantages of this solution are: a harder control of the voltage level at high speed, problems on fixing the magnets; the high temperature level and the necessity of using special materials. This inconveniences encouraged the orientation of study in finding other solutions. In this direction it is studied the possibility of substitute the classic generator by a hybrid synchronous generator (HSG), which uses permanent magnet and electromagnetic excitation [4]. The power generated by this H.S.G. can be of 4kW and it operates between large limits of speed. The use of permanent magnets makes this generator to be more efficient, by reducing the cooper loses in excitation windings.

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This paper presents the results obtained by numerical methods, using finite element method on a hybrid synchronous generator model and compares these results with experimental data achieved by acquisition.

2. THE H.S.G. IMPLEMENTATION SYSTEM

The studied H.S.G. is used to generate electric power for supplying the islanded users installed in places that are not accessible to the centralised electrical distribution system. It can be driven by an engine or by unconventional supply systems. The generated three phase voltage system is rectified by means of a diode bridge (Fig.1).

![Fig. 1 – Electric circuit of the generator with voltage regulator.](image)

The produced power is used to charge the battery assembly and to supply the existing users with electric energy.

No matter the H.S.G. under-load or no-load operates, the generated voltage level should be at constant value, not less than battery voltage. The voltage level can be maintained constant at speed or load variations by increasing or decreasing the excitation current ($I_{ex}$). This is possible by modifying the field resistor ($R_f$) through an electronic switch ($K_u$) controlled by an electric relay [4].

The relay coil ($B_u$) is controlled by a voltage, which is proportional with the alternator generated voltage. If the voltage level goes below the value of battery voltage, the signal lamp indicates “battery not charge”. At the same time, the relay coil ($B_u$) voltage is under the control level, $K_u$ is closed and $R_f$ short-circuited. The excitation current ($I_{ex}$) is at maximum level maintaining the voltage generated by
the generator at a constant level. Now, the relay coil \((B_u)\) has a self voltage drop sufficiently to command the relay and to open the electronic switch \(K_u\), which connects the field resistor \((R_f)\) of the excitation circuit and limits the current level.

3. F.E.M. STUDY OF H.S.G

3.1. CONSTRUCTIVE PARAMETERS OF H.S.G.

The H.S.G. construction differs to a classic synchronous generator. Actually, this H.S.G. includes two different types of electric machines: a synchronous machine with permanent magnet excitation and a synchronous machine with electromagnetic excitation system. These two machines have different magnetic circuits, physically separated, and a commune stator winding, placed into aligned slots. Fig. 2, presents the construction of the studied H.S.G.

![Fig. 2 – Hybrid synchronous generator.](image)

Both components of the H.S.G. have 36 stator slots, a three-phase star connected stator winding with one slot per pole per phase, and 12 poles. Each slot has 16 series connected turns. The coils have a pole pitch of \(y = 3\). The length of the part with electromagnetic excitation is of 35mm and for the permanent magnet part is of 45mm. The cross sections of these two practical different machines that are included in the H.S.G. are presented in Flux 3D geometry in Fig. 3 and Fig. 4.
3.2. USING FLUX2D SIMULATION

Because of the great volume of work and the limitation of data computation systems, for simulation, we used 2D model of each machine (one with the electromagnetic excitation, and one with the permanent magnet excitation) that compose the H.S.G. instead of 3D module.

The two models have been separately analyzed and the final results took into consideration the rule of addition of the effects. For this purpose, we have followed the following steps: building of the geometries, allocation of the materials, mesh generation. Then, define of the electric circuit and assigning of the boundary conditions.

The simulation consisted in a transient magnetic analysis, corresponding to a no-load operation with an excitation current of 3A and a speed of 3 000 rot/min. Subsequently, other simulations have been made for different operation conditions: constant excitation current in the range of $I_{ex} = -5A \ldots +5A$ and different speeds (500; 1 000; 1 500; 2 000; 2 500; 3 000) rpm, in order to obtain the voltage with speed characteristics, $U = f(n)$, for no-load operation, and the voltage and current characteristics for a equivalent load of $R_l = 10\Omega$.

3.3. SIMULATION RESULTS

After the solving process, the following field distributions were obtained for each model (Fig. 4). A particular interest is represented by the flux density distribution into the air gap and its spectral analysis (Fig. 5). The r.m.s. values of the flux density are of 0.75T and 0.47T respectively.
Fig. 4 – Flux lines distribution: a) electromagnetic excitation; b) permanent magnet excitation.

Fig. 5 – Air-gap flux density and Fourier analysis: a) em. excit.; b) pm. excit.

The waveform presents high order harmonics caused by the number of stator and rotor slots. In this case the slots are axial orientated. This is the reason for the appearances of the 3rd, 5th, 7th, 11th and 13th harmonics. An important decreasing of these harmonics can be achieved by modifying the rotor slots geometry or skewing the stator slots (complicated solution). The different values of the first order harmonics is a result of the excitation current which deliberately has a smaller
value. As a matter of fact, the electromagnetic excitation has an auxiliary function, mainly for adjusting the output voltage.

3.4. EXPERIMENTAL RESULTS AND COMPARISON WITH SIMULATION

The waveform of the phase, line and rectified voltage, obtained by simulations (Fig. 6) can be compared with those obtained by acquisitions (Fig. 7) for no-load operation. It can be observed that the simulation error is less than 5%.

![Phase, line and rectified voltage, obtained by simulation.](image1)

**Fig. 6** – Phase, line and rectified voltage, obtained by simulation.

![Phase and rectified voltage obtained by acquisition.](image2)

**Fig. 7** – Phase and rectified voltage obtained by acquisition.
The wave form of the induced voltage in the permanent magnet excitation machine looks like the variation of the flux density of the permanent magnet part. When the rotor pole shoe intercrosses the stator coil section, then appears an important variation of the magnetic flux, which explains the rapidly increasing of the induced voltage.

The results obtained by simulation allow us to plot the $U = f(n)$ characteristics, for different excitation currents (Fig. 8). It can be observed that the voltage has a linear variation with speed.

![Graph showing $U = f(n)$ characteristic for different excitation currents ($I_{ex}$).](image)

Fig. 8 – Simulated $U = f(n)$ characteristic, for different excitation currents ($I_{ex}$).

![Graph showing phase and load current from simulation.](image)

Fig. 9 – Phase and load current from simulation.
Fig. 9 and Fig. 10 present the waveform of the phase current and the load current, obtained by simulation and acquisition, for the under-load operation.

3.5. CONSTRUCTIVE SOLUTIONS FOR VOLTAGE LEVEL VARIATION

The voltage level generated by this machine can be modified through a particular design of the stator winding. For this purpose, the winding, which is a double layer one with one slot per pole per phase, has only one turn fall into eight conductors. The ends of the conductors are accessible and connected to a terminal board. This fact allows different series, parallel or multiple series-connections.

Fig. 11 – Stator winding (A-X phase) and section on the turns.
Fig. 11 presents the stator winding for one phase (A-X). It has to be specified that each phase winding does not start or finish under the same pole. Section $\alpha$ of this figure shows the ends (a1-a8) of the eight conductors of the coil. There are also noted the slot numbers of the represented phase winding.

Practically, four connections are possible: 8 conductors parallel connected, 2 parallel connected sections of 4 series connected conductors, 4 parallel connected sections of 2 series connected conductors and 8 conductors series connected. Each connection differs to each other with the number of paths: 8 paths and 1 conductor per path, 2 paths and 4 conductors per path, 4 paths and 2 conductors per path and 1 path with 8 conductors per path respectively.

![Fig. 12 – The equivalent circuits.](image)

![Fig. 13 – $U = f(n)$: 1 – series; 2 – series-parallel; 3 – parallel.](image)

Each path consists of a series connected group of coils, each coil possessing a generated voltage level. The voltage level of the generator is determined only by the approximate equal number of series connected coils per path and not by the
number of paths in parallel. As the number of paths is increased, the current level of
the generator is increased. For any given number of conductors, increasing the
number of series connected coils per path leads to an increase of the voltage and to
decrease of the output current through decrease of the parallel paths number.

Fig. 12 presents three of the four presented situations, which have been tested
on the test bench and Fig. 13 presents the $U = f(n)$ characteristics that put in view
the different voltage level.

4. CONCLUSIONS

The F.E.M. simulation allows us to modify different constructive parameters,
such as: geometric dimensions, turns number, material proprieties, in order to
obtain electric quantities imposed by working conditions and validated on the test
benches. This simulating error might be caused by the approximations used in 2D
simulation. For better results, a 3D approach could be useful.

The linear variation of the output quantities with speed represents a real
advantage to the voltage, speed or current regulator. The analysis of the phase
voltage wave form indicates the high order harmonics contents.

The construction of the machine in two distinct parts, one with permanent
magnet and electromagnetic excitation enlarge the voltage range and consequently
is more flexible for different consumers.

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