MAGNETIC FIELD IN THE AIRGAP OF THE THREE-PHASE SYNCHRONOUS GENERATOR CONNECTED ON RECTIFIERS

Corneliu NICĂ, Monica Adela ENACHE

Faculty of Electromechanical Engineering, University of Craiova
107, Decebal Street, 200440 Craiova (Romania)
e-mail: cnica@em.ucv.ro, menache@.em.ucv.ro

Abstract - **In the paper there is developed the method of analysis of the three-phase synchronous generator - rectifier system and there is analysed the distortion degree of the magnetic quantities specific to the generator. The concordance of the theoretical results with those obtained experimentally - for a synchronous generator of average power - proves that the analysis method is correct. The method of study can be used for the synchronous motors supplied by static converters too, the difference consisting just in the way of determination of the r. m. s. value and of the superior harmonics of the currents through the phases of the armature winding.**

Keywords: *synchronous generator, rectifiers, magnetic field, harmonics.*

1. INTRODUCTION

The extension of the synchronous generator - static converter systems is commanded in principle, by the high investments on the world plane in the field of the excitation systems for the high power alternators, of the land and sea drilling, of the road and rail high capacity transport, of the aerial and water transport, of the transport systems of electrical energy, in direct current (d. c.).

The association between synchronous generators (SG) and rectifiers (R) has direct implication on the rectifiers operation, but also on the technical and economic performances of the generators and the analysis of their operation can be done only through unitary observation of the whole system. The new aspects occurring in the operation of the synchronous generator - rectifier (SG-R) system have formed and are still forming the object of some theoretical and experimental investigations [1, 2, 3], in order to provide some superior performances. Among them, a special importance has got the computation of the supplementary losses caused by the presence of the superior harmonics of the windings currents and of the field in different parts of the magnetic circuit.

2. THE STATIONARY REGIME OF THE SYNCHRONOUS GENERATOR – RECTIFIER SYSTEM OPERATION

The spatial distribution of the flux density into the electrical machines airgap is mainly determined by the m. m. f. curve, to which the influence of the magnetic circuit configuration and of the slots presence are added. In a general case, when the windings currents are non-sinusoidal, the curve of the flux density can be expressed as a double series of space and time harmonics.

The magnetic field in the airgap of the three-phase electrical machines, operating in symmetrical and sinusoidal conditions, is analysed in details in the speciality literature. Further on only the space fundamental of the airgap field is taken into account and there are analysed the superior time harmonics determined by the rectified load.

The GS-R system operation is characterized by the periodical alternation of the intervals with commutation of the currents between the generator phases with intervals without commutation. The determination of the magnitude and of the waveform of the field in different parts of the magnetic circuit is a complex problem, but it is important for the determination of the supplementary losses caused by the distorting regime.

The method for the analysis of the synchronous generator - controlled rectifier system is developed in [2] on the basis of the decomposition of the armature winding currents in harmonics and by solving the differential equations system of the generator - written in the *d, q* axes system [1, 4] - for each harmonic up to the order 25. The equations are written in complex form because the harmonics have sinusoidal time variation. The method need utilization of the computer and it provides directly the harmonics of the rotor windings currents and of the magnetic field, necessary for the computation of the supplementary losses, of the efficiency and of the power factor.

The currents curves through the armature three-phase winding, connected on a controlled bridge rectifier, contain superior harmonics of order

$$n = 3k_R k \pm 1; \qquad k = 1,2,3........, \tag{1}$$

in which $k_R = 1$ for half-controlled bridge rectifiers and for null point rectifiers, and $k_R = 2$ for controlled bridge rectifiers. In the hypothesis of the perfect filtration of the rectified current, it is possible

to establish the r. m. s. value, I_n, and the phase, Ψ_{in}, for the superior harmonics of order n of the currents through the armature winding phase, with the help of the relations or curves of the commutation functions, $F_n(\alpha,\gamma)$, from [5], in which α is the command angle and γ - the commutation angle of the thyristors.
The fundamental time harmonic of the currents through the armature winding determines the reaction field, which interacts with the inductive field, with already known effects [1,6].
The superior harmonics form symmetrical three-phase systems of reverse succession ($n' = 3k_Rk - 1$) and of direct succession ($n'' = 3k_Rk + 1$). To them there correspond in the d, q axes system the components $i'_{d\nu}$, $i'_{q\nu}$ and $i''_{d\nu}$, $i''_{q\nu}$, having the frequency $f_\nu = \nu f_1$, where $\nu = 3k_Rk$, represent the harmonics order in the d, q axes system. In order to avoid the obtaining of some non-linear equations systems, too difficult and with great proportions, certain factors of secondary importance are neglected, an idealized machine being obtained.
By considering the common action of the resultant currents, having the same frequency, f_ν,

$$i_{d\nu} = i'_{d\nu} + i''_{d\nu};$$
$$i_{q\nu} = i'_{q\nu} + i''_{q\nu}, \qquad (2)$$

the equations of synchronous machine, in relative units, can be written in the form [2,3]:

$$u_{d\nu} = -R_\nu i_{d\nu} - \frac{d\Psi_{d\nu}}{dt} + \varpi\Psi_{q\nu}$$
$$u_{q\nu} = -R_\nu i_{q\nu} - \frac{d\Psi_{q\nu}}{dt} - \varpi\Psi_{d\nu};$$
$$0 = R_{Dd\nu} i_{Dd\nu} + \frac{d\Psi_{Dd\nu}}{dt}; \qquad (3)$$
$$0 = R_{Dq\nu} i_{Dq\nu} + \frac{d\Psi_{Dq\nu}}{dt};$$
$$0 = R_{f\nu} i_{f\nu} + \frac{d\Psi_{f\nu}}{dt},$$

where

$$\Psi_{d\nu} = X_{\sigma\nu} i_{d\nu} + X_{ad}\left(i_{d\nu} + i_{f\nu} + i_{Dd\nu}\right);$$
$$\Psi_{q\nu} = X_{\sigma\nu} i_{q\nu} + X_{aq}\left(i_{q\nu} + i_{Dq\nu}\right);$$
$$\Psi_{f\nu} = X_{ad} i_{d\nu} + X_{f\nu} i_{f\nu} + X_{fDd\nu} i_{Dd\nu}; \qquad (4)$$
$$\Psi_{Dd\nu} = X_{ad} i_{d\nu} + X_{fDd\nu} i_{f\nu} + X_{Dd\nu} i_{Dd\nu};$$
$$\Psi_{Dq\nu} = X_{aq} i_{q\nu} + X_{Dq\nu} \tilde{i}_{Dq\nu}.$$

The notations from [1, 3, 4, 5] have been used in the equations presented before.
The expressions of the rotor windings currents and of the linkage fluxes in different parts of the magnetic circuit are obtained by writing in complex form the equations (4) and by solving them relatively to the harmonics of the stator currents. The superior harmonics values of the magnetic flux density are determined with their help.

3. COMPUTATION AND EXPERIMENTAL RESULTS

An analysis of the field in different parts of the magnetic circuit of a three-phase synchronous generator, connected on rectifier, is carried out further on. There are taken into account the results of the numerical computation and of the experimental tests carried out for a SG rated at: 265*kVA*, 400*V*, 380*A*, 50*Hz*, 1500*rpm*. Its rotor has salient poles and it has been fitted out with a longitudinal-transversal damping winding having 9 copper bars on a pole. To the SG terminals have been successively connected a three-phase controlled bridge rectifier (CBR3), a three-phase half-controlled bridge rectifier (HCBR3), respectively. Both rectifiers have supplied a d. c. motor.
The distortion degree of the magnetic quantities specific to the GS has been emphasized through the e. m. f. induced into the test turns that have been assembled:
a) - on the stator:
s_1 – space filter corresponding to the space fundamental harmonic of the airgap flux density. This space filter has the conductors placed sinusoidally on the internal side of the stator, with a wavelength equal to that one of a pole pitch [6]. By measuring the harmonics of the voltage to the turn terminals there are obtained the time harmonics of the airgap flux density.
s_j - ring-turn round the stator magnetic circuit, having the sides parallel to the slots (one - in the exterior of the stator yoke and another one in the airgap, on the level of the inner diameter of the stator).

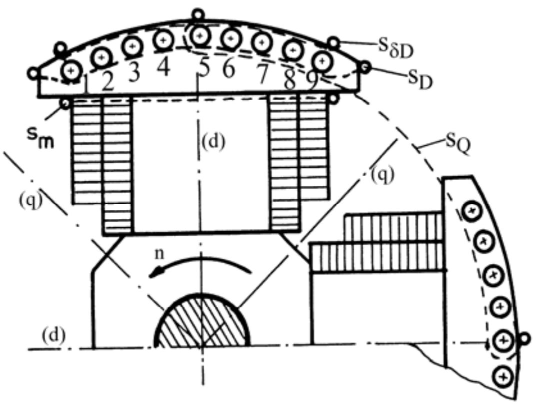

Fig. 1. Disposition of the test turns on the rotor and numbering of the damping winding bars.

b) - on the rotor (Fig. 1):

s_{m}, s_{D}, $s_{\delta\mathrm{D}}$ – coaxial turns with longitudinal axis;

s_{Q} - coaxial turn with transversal axis.

An image of the time variation of the flux density corresponding to the resultant field in the airgap and in the stator yoke can be proved by the oscillograms of the e. m. f. induced in the filter-turn, u_{s1} and also in the ring-turn, u_{sj}.

When the SG operates without load and excited, the e. m. f. u_{s1} has sinusoidal time variation and the e. m. f. u_{sj} has rectangular time variation. When the SG operates with load, the curves depart from these variation forms (Fig. 2). The time variation forms of the e. m. f. induced in the test turns from the rotor are presented in the Figure 3.

The r. m. s. values of the harmonics of the e. m. f. U_{s1n}, induced in the turn s_1, have been measured with the help of a harmonics analyser and on the basis of the relation [6]

$$B_{\delta n} = \frac{\sqrt{2}U_{s1n}}{nM\tau\varpi_1} \qquad (5)$$

there have been determined the amplitudes of the time harmonics of the airgap resultant field density.

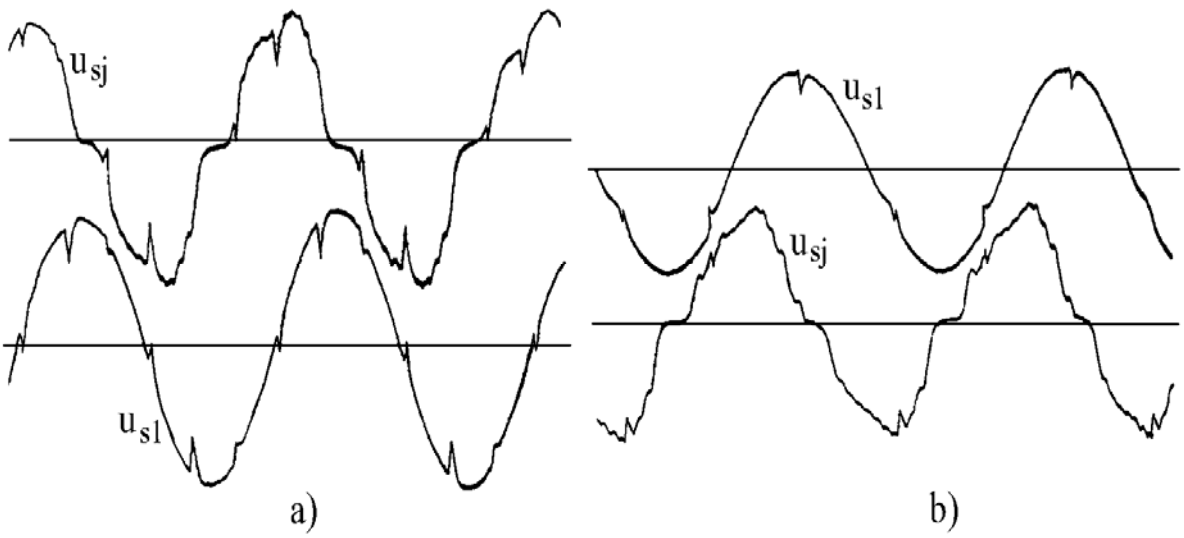

Fig. 2. Oscillograms of the e. m. f. induced in the test turns on the stator, for $I_{\mathrm{dc}} = 250A$, $\alpha = 60^{\mathrm{o}}$ and two variants of the rectifier: a) – CBR3; b) – HCBR3.

There have been noted: M the space amplitude of the turn distributed sinusoidally, τ - the polar pitch, n – the time harmonics order and ω_1 - the angular frequency corresponding to the time fundamental. In the Table 1 there are given the relative values of the flux density, $B_{\delta n} / B_{\delta 1}$, computed and determined experimentally.

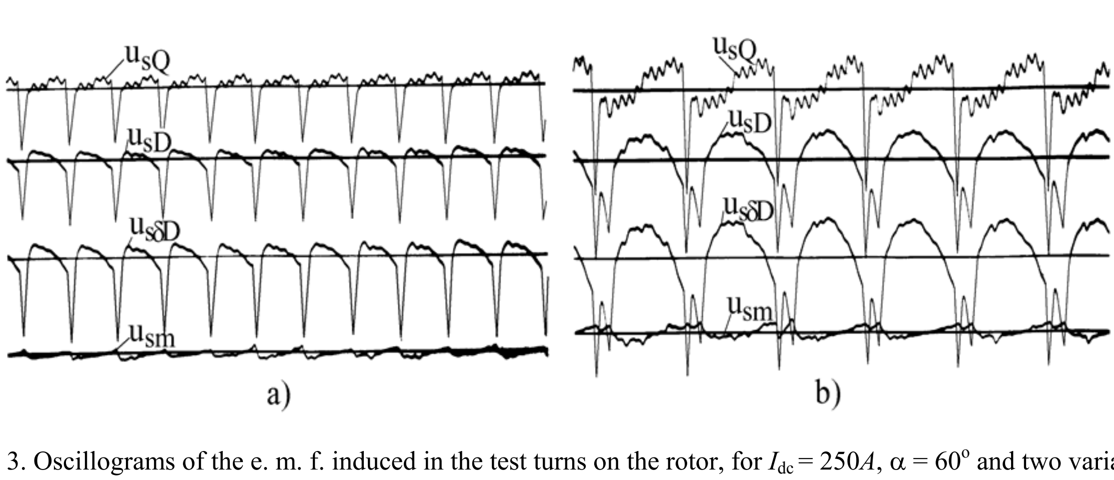

Fig. 3. Oscillograms of the e. m. f. induced in the test turns on the rotor, for $I_{\mathrm{dc}} = 250A$, $\alpha = 60^{\mathrm{o}}$ and two variants of the rectifier: a) – CBR3; b) – HCBR3.

Rectifier variant	α $[^0]$	$B_{\delta n}/B_{\delta 1}$								
		n / Values	2	4	5	7	8	10	11	13
CBR3	5	calcul.	-	-	0,021	0,018	-	-	0,008	0,007
		measur.	-	-	0,02	0,017	-	-	0,009	0,007
	60	calcul.	-	-	0,041	0,034	-	-	0,02	0,014
		measur.	-	-	0,038	0,032	-	-	0,018	0,013
HCBR3	60	calcul.	0,096	0,086	0,028	0,025	0,013	0,013	0,011	0,012
		measur.	0,09	0,083	0,03	0,022	0,013	0,012	0,011	0,011
	90	calcul.	0,116	0,012	0,041	0,043	0,02	0,022	0,01	0,013
		measur.	0,112	0,012	0,041	0,041	0,019	0,02	0,01	0,012

Table 1. The values of the airgap flux density harmonics, in relative units, for $I_{dc} = 250A$.

4. CONCLUSIONS

The method presented before and the achieved computation program allow the determination of the superior harmonics of the airgap magnetic field of the synchronous generator connected on rectifiers, with a satisfactory precision for the computation of the supplementary losses and of the harmonics content in the voltage curves to the terminals.

By analyzing the curves of the e. m. f. induced in the test turns (Fig. 2 and Fig. 3) we can mention the following conclusions:

- the harmonics content of the airgap flux density (Tab. 1) is somehow decreased in the case of a well-dimensioned damping winding;
- the harmonics of the magnetic field in the poles core are approximately negligible (see e. m. f. u_{sm} – Fig. 3); this thing proves that the damping winding represents a screen for the superior harmonics;
- in the rotor teeth there is actually only the leakage field of the damping winding bars, for superior harmonics;
- in the case of HCBR3, when the angle α increases, the harmonics of order 2 and 4 of the stator current also increase, making to occur the order 3 harmonics in the rotor quantities; this aspect is emphasized by modifying the frequency of the e. m. f. induced in the turns from the rotor (Fig. 3.b).

The distorting regime is more striking when using the half-controlled bridge rectifier; that is why, its utilization is not justified in the case of the autonomous synchronous generators.

References

[1] A. Câmpeanu, *Maşini electrice (Electrical Machines)*, Editura Scrisul Românesc, Craiova, 1988.

[2] C. Nică, *Operating Characteristics in Sdeady-State Regime of the Synchronous Generator Asociated with Rectifiers* Proc. ICEMADS'86, Eforie Nord, 16-17 September, 1986, Vol. I, pp.56-62.

[3] C. Nică, *Contribuţii la studiul funcţionării generatorului sincron în comun cu convertoarele statice (Contributions on the Study of Operation of Sychronous Geenrator in common with the Static Converters)*, Teză de doctorat, Universitatea din Braşov, 1987.

[4] A. Nicolaide, *Maşini electrice (Electrical Machines)*. Vol. II. Editura Scrisul Românesc, Craiova, 1975.

[5] Gh. Drăgănescu, *Încercările maşinilor electrice rotative (Testings of Rotative Electrical Machines)*. Editura Tehnică, Bucureşti, 1987.

[6] H. Frohn, *Synchronmaschine Moglichkeiten der experimentellen Analyse de Luftspaltfeldes electrischer Mashinen*, E. T. Z. A, Vol. 90, No. 4, 1969.