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ON THE MODULATED CONDUCTIVITY INDUCTION SYNCHRONOUS MAGNETOGASDYNAMIC GENERATOR

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In the earlier publications[1,2] a preliminary analysis of the operation of several modifications of an induction synchronous MGD- generator has been presented. It has been stated that certain variants of these generators will be effective independently of the magnitude of magnetic Reynolds number evaluated for the medium flow in the generator duct. A criterion has been formulated indicating the conditions needed for those variants.

This paper reveals some results of a more detailed examination[3] concerning the operation of a synchronous generator fed with a jet of varying conductivity working medium, where the mentioned criterion is complied with.

1. The generator in question is shown schematically in Fig. 1. The working duct, a rectilinear circular cylinder enclosed in a ferromagnetic core of high permeability, is furnished with ferromagnetic ribs connecting the inner and outer core in the end- parts of the duct. The generator is provided with two kinds of mutually independent windings, namely: the field coils wound circumferentially on both walls of the duct, and the output coil. The last may be located in any position along the duct provided it will enclose the whole induced magnetic flux Φ passing the generator core. The generator load connected to the output coil consists of a resistance R_l and a compensating capacitance C in parallel. The field coils, fed with direct current from an external source, have a special distribution of their number of turns along the generator duct in order to make the generated field of magnetizing induction B_m (which, in principle, is directed radially) approximately sinusoidal. The stream of working medium, flowing in the direction of x- axis in the generator duct consists, alternately, of: "conductive portions" having electric conductivity $\sigma = \sigma_p$ and "non-conductive portions" $\sigma = 0$ of fluid. The mean velocity of this flow is a function of coordinate, and additionally a condition is imposed on the distances among subsequent conductive portions to be (with x given) approximately equal to the period l of the function B_m. The period l itself may vary with x. Segments of the generator length, each enclosing one period of variation of the induction B_m (measured from zero- points), will be referred to as generator sections. The generator will, thus, be assumed to consist of N sections.

2. At first, we consider a single (s-th) section of the generator. Assuming that the duct dimensions, flow velocity and conductivity of conductive portions will not vary remarkably within the limits of one section, we are able to characterize the operation of this section by the following relations:

$$P_{0s} = \frac{1}{2}\,\frac{\omega^2 \Phi_s^2}{R_p}\,\frac{\alpha_s}{\left(\frac{\alpha_s}{Q_s}\right)^2+(1+\alpha_s)^2} \qquad (1)$$

$$\frac{1}{\eta_s}-1 = C_2\frac{1}{\alpha_s}\left[\left(\frac{\alpha_s}{Q_s}\right)^2+1\right]+(C_2-1)(\alpha_s+2) \qquad (2)$$

where
- P_{0s} - output power of the section
- η_s - electrical efficiency of the section, resulting from joulean heat losses only
- ω - circular frequency of the generated current
- Φ_s - characteristic value of the magnetizing flux crossing the duct, in the considered section
- R_p - effective resistances of the different conductive portions, within the s-section
- $C_2 \geqslant 1$ - numerical coefficient depending on duct dimensions and on the quotient l_p/l (cf. Fig. 1)
- α_s - local load coefficient
- Q_s - local quality factor

The relations (1), (2) are illustrated graphically in Fig. 2 and 3.

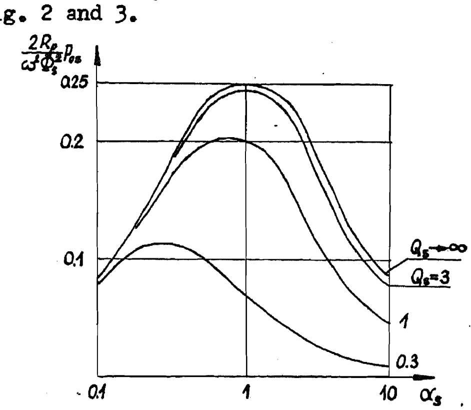


Fig.2.

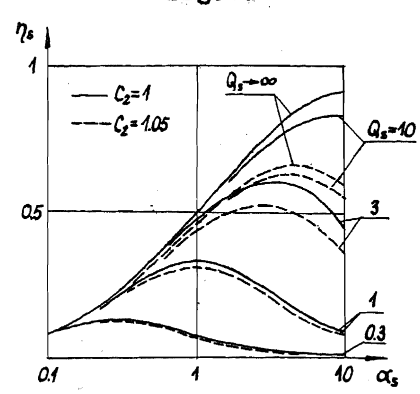
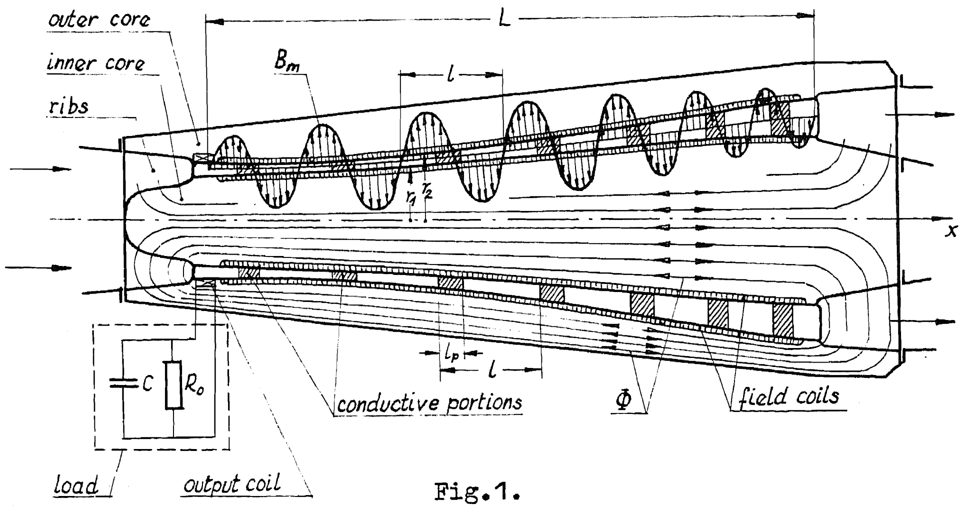


Fig.3.



outer core
inner core
ribs
B_m
L
l
r_1
r_2
x
C
R_o
l_p
l
conductive portions
Φ
field coils
load
output coil

Fig.1.

Now, it is possible to calculate the electrical characteristics of the generator as a whole. The generator output power P_o and electrical efficiency η may be expressed by P_{os} and η_s, in a simple summation

$$P_o = \sum_{s=1}^{N} P_{os} \qquad (3)$$

$$\eta = \frac{\sum_{s=1}^{N} P_{os}}{\sum_{s=1}^{N} \frac{P_{os}}{\eta_s}} \qquad (4)$$

but the relations (3) and (4) will be useful only if α_s and Q_s coefficients are expressed through other parameters which may be controlled directly.

Assuming that there are no phase shifts of electromotive forces between the different sections, the following relations may be obtained

$$\alpha_s = \frac{1}{\frac{\Phi_s}{\Phi_o}\left(\frac{1}{\alpha}+1\right)-1} \qquad (5)$$

$$Q_s = \frac{\Phi_o}{\Phi_s} Q^* \qquad (6)$$

where

$\Phi_o = R_i \sum_{s=1}^{N} \frac{\Phi_s}{R_p}$ - mean magnetic excitation flux

$R_i = \frac{1}{\sum_{s=1}^{N} \frac{1}{R_p}}$ - resultant internal resistance of the generator

$\alpha = \frac{R_o}{n^2 R_i}$ - generator load coefficient (R_o - load resistance, n - number of windings of the output coil)

$Q = \frac{\omega}{R_i \mathcal{R}}$ - design quality factor of the generator ($\mathcal{R}$ - core reluctance against induced flux Φ)

$Q^* = \frac{Q}{1-\frac{Q}{\alpha}\omega R_o C}$ - effective quality factor of the generator (C - compensating capacitance, in parallel with R_o)

The quantities Φ_s, ω and Q are among those of the most important design parameters, while α and Q^* - represent main working parameters of the generator.

Now the generator output power may also present itself as the relation

$$P_o = \frac{1}{2}\frac{\omega^2 \Phi_o^2}{R_i}\frac{\alpha}{\left(\frac{\alpha}{Q^*}\right)^2+(1+\alpha)^2} \qquad (7)$$

and the reactive power "consumed" by the compensating capacitor C as

$$P_r = \left(\frac{\alpha}{Q} - \frac{\alpha}{Q^*}\right) P_o \qquad (8)$$

In case of the generator connected to a rigid power network instead of an isolated load, the expressions (5) and (6) must be replaced by other ones, but the nature of physical phenomena does not alter. The expressions (7) and (8) will still be valid but the quantities α and Q^* will in this case depend on the grid voltage U, flux Φ_o and generator phase angle φ.

The resistance R_p is inversely proportional to the electrical conductivity of σ_p of conductive portions, in accord with the relation

$$R_p = \frac{2\pi r_l}{\sigma_p l_p d} \qquad (9)$$

where $d = r_2 - r_1$ - working duct width, r_l - logarithmic mean radius of the duct.

The determination of quantities σ_p and l_p represents, in general, a problem in itself where the kind of the working medium used is of main importance. If ionized gases (due to thermal or non-thermal ionization) were assumed to form the conductive protions of the working medium, then the ionization and deionization phenomena, diffusion and turbulence, instability etc. would be decisive in the σ_p and l_p variation along the generator duct. The life of conductive portions would in this case be sustained by way of an appropriate feeding of additional power or fuel from outside, and by issuing of internal power $P_{os}\frac{1-\eta_s}{\eta_s}$.

The quantity P_o established by relations (3) and (7) determines the gross power of the generator. A number of additional losses, besides the joulean loss in the working medium, will occur in an actual generator. These are the losses in the ferromagnetic core in the main, and possibly the above mentioned losses due to the stimulation of conductive portions. The net generator power will, therefore, be expressed by the relation

$$P_o' = P_o - P_d = \left(1 - \frac{P_d}{P_o}\right) P_o \qquad (10)$$

and the actual generator efficiency

$$\eta' = \left(1 - \frac{P_d}{P_o}\right)\eta \qquad (11)$$

where P_d - resultant power of additional losses.

As follows from Fig. 2 and 3 the section quality factor Q_s is to be in extent of $Q_s \sim 10$ and l_p should not exceed one seventh of the period l, if it is intended to attain high efficiency of the section e. g. $\eta_s > 0.5$. The proportions of the remaining dimensions, if kept in reasonable limits, are of minor importance. If all the sections of the generator differ but slightly then: $\alpha_s \approx \alpha$, $\rho_s \approx \rho$, $P_c \approx N P_{cs}$ and $\eta_s \approx \eta$. Then also the theoretical feasibility of $Q_s \approx Q^* \geqslant 10$ becomes apparent independently of the value of Q, provided an adequate value of the compensating capacitance C is applied. However, the application of relatively high values of the design quality factor Q would be mostly desirable, and even indispensable in a generator of great output for power production purposes, as in such a case the reactive power P_r should not be excessive. According to (8) the reactive power P_r is proportional to α/Q when $Q^* \gg \alpha$. Therefore, if the condition $P_r < P_o$ is to be met than $Q > \alpha$ must occur, i.e. the core reluctance R and the resistance of conductive portions R_c cannot exceed certain maximal values. Thereby, the conductivity of conductive portions σ_c and the permeability of core μ_c must have sufficiently high values for the generator to be practical. Provided $Q > \sim 10$ was achieved, the generator would operate effectively even without any compensation, i.e. with $C = 0$, and of course $P_r = 0$. This case should be regarded as optimal variation.

3. It is interesting to compare the synchronous generator with other types, particularly with the well-known electrode d.c. generator, and also with the asynchronous induction generator [4].

Confronting one section of the considered generator (having the length l_p sufficiently small and a high value of the quality factor Q_s) with an equivalent section of the d.c. generator, where working duct volumes, medium velocities and conductivities, as well as maximal values of the field induction are identical, we obtain

$$P_{os} \cong \frac{1}{2} \frac{l_p}{l} P_{d.c.} \qquad (12)$$

having in mind that the medium electrical conductivity in the d.c. generator is constant. The numerical coefficient 1/2 in (12) results from the application of induction B_m varying sinusoidally along the duct of the synchronous generator, contrary to the constant B_m in the d.c. generator. The factor l_p/l is due to the conductive portions filling the duct of the generator in question not completely, as the medium conductivity in the d.c. generator is not modulated. Core losses, that may affect the a.c. generator seriously, do not take place in a d.c. generator. On the contrary, the generator at issue shows neither electrode losses nor the disadvantages of the Hall's phenomenon, since the Hall voltages appearing in conductive portions yield no adverse effects. Furthermore, the synchronous generator will have a more complicated working duct than the d.c. one, with the intricate configuration of magnetic field and the coils located on both walls (especially if the width of that last is considerable). These properties together with the presence of core would impede the application of superconducting coils and the very large field inductions (exceeding the induction of core saturation). It should also be mentioned that a "conventional" d.c. generator with segmented electrodes may (theoretically) be converted into an a.c. generator, provided the modulation of conductivity is introduced.

The layout and working characteristics of an asynchronous generator with travelling wave magnetic field are, to some extent, similar to those of the contempleted synchronous generator. All the same there are two essential points of difference to be considered:

- in a synchronous generator the modulated conductivity working medium flow is indispensable, whereas with an asynchronous generator constant conductivity may be used,
- an asynchronous generator needs a much (several orders of magnitude) higher value of the working medium conductivity than the synchronous generator.

A more detailed analysis of the nature of these generator working processes shows that the magnetic Reynolds number should, in an effective asynchronous generator, exceed some minimum (of the order of $R_m \sim 1$). At the same time R_m should not be too high, because some detrimental effects of non-linearity may occur (especially at high generator loads). The synchronous generator will work effectively independently of R_m - value (with $R_m \ll 1$ and with $Rm \gg 1$ as well) as in this case the core interaction parameter R_c [1], instead of R_m, is acting here as the basic physical parameter, and non-linear effects do not turn up. It is much easier to attain in practice the desired minimum of R_c (which is also of the order of $R_c \sim 1$) in a synchronous than the minimum of R_m in an asynchronous generator, since, roughly, the following relation applies

$$R_c \sim \frac{\mu_c}{\mu} R_m \qquad (13)$$

where μ - permeability of the generator duct. Insufficient values of R_m in one, and R_c in the other of the generators will equally require compensation by the reactive power P_r of the generator, and here the P_r - value will increase with the dropping of the R_m - or R_c - value.

In conclusion, the principal difference between the asynchronous and the synchronous generator is that the first meets, and the second does not meet the criterion of applicability of low Reynolds numbers [2], mentioned at the very beginning of this paper. In addition, it should be noted that in the other possible variants of a synchronous generator [1] the above criterion is not satisfied, and therefore the application of large R_m - values would be indispensable for them.

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