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SUPERSATURATED SYNCHRONOUS MACHINE DESCRIPTION AND MODELISATION

A. Mailfert, A. Rezzoug and P. Manfe

Groupe de Recherche en Electrotechnique et Electronique de Nancy (G.R.E.E.N.), E.N.S.E.M., 2 rue de la Citadelle, 54040 Nancy Cedex, France

RESUME - Les auteurs décritent et analysent un nouveau type de machine synchrone supraconductrice dans laquelle la bobine supraconductrice est fixe. Après en avoir évalué les performances en couple volumique, les auteurs indiquent l'état d'avancement de leur programme expérimental.

ABSTRACT - A new concept of cryogenic synchronous machine is described and analysed. In this type of machine, the superconducting coil is motionless. In this paper, after an evaluation of the unit volume torque, a comparison with a conventional high power high number of poles machines is made. The last part is devoted to indications about the experimental program under development.

I - INTRODUCTION

The application of superconductors to a.c machines with a low number of poles is now widely studied in many countries /1/. Our paper deals with a new concept of superconducting machine adapted to the design of a high number of poles a.c machine. In this concept, a large volume of room-temperature ferromagnetic material (such as iron or iron - cobalt alloy) is conveniently shaped in order to create a multipole configuration of magnetic field when it is polarised by the field of a superconducting solenoid. The rotation of the ferromagnetic material is used to obtain e.m.f. at the terminals of a room temperature multipole armature winding. The best performances are obtained if the iron is deeply saturated (SUPERSATurated)

In this paper, will be presented:
- The general concept of SUPERSAT a.c. machine /2/.
- The theoretical evaluation of the torque per unit volume and a comparison with conventional high power, high number of poles a.c. machines.
- Some indications about prototype SUPERSAT 01 under construction.

II - THE GENERAL CONCEPT OF SUPERSAT A.C. MACHINES

In accordance with the principle described in the preceding introduction, the main elements of SUPERSAT a.c. machine are the following (Fig.1):

![Fig 1 - Schematic diagram of SUPERSAT a.c. machine](http://dx.doi.org/10.1051/jphyscol:19841148)
- A superconducting solenoid (1) with a room temperature working zone.
- Several rotating discs (2) locked on the shaft (3) of the machine; each of them fitted with \( p \) large iron plugs.
- Fixed armature (4) discs with 2 \( p \) poles number and \( q \) phases number interleaved with the rotating discs. In order to reduce eddy currents, the elementary conductors are finely divided, as those of large superconducting generators /3/.
- An electromagnetic screen (5) is provided by a conducting cylinder, just at the periphery of the room temperature working zone. It protects the superconducting coil against the fringing fields of the central part.

Assuming that:
- the plug material is supersaturated, with a saturation value of magnetization \( \mu_0 M_s \)
- the \( z \)-period \( 2b \) of the discs and armature windings is much lower than the pole pitch \( \tau_p \)
- the length \( L \) of the machine is well above \( \tau_p \)

it is easy to show that the maximum peak to peak variation of the axial induction is:

\[
(\Delta B)_{\max} = \frac{a}{b} \mu_0 M_s \quad (1.1)
\]

It will be shown that an optimal value of power is obtained when \( 1/2 < \alpha < 1 \). The classical values \( \mu_0 M_s \),\( 2T \) (iron) or \( \mu_0 M_s \),\( 4T \) (Fe-Co) show that the maximum \( (\Delta B) \) values are limited in the range of 1.1-2.2T (or 1.2-2.4T) in the SUPERSAT concept. Compared to the corresponding values of 2T classically realized in the conventional multipole a.c machine, this result would seem to show that SUPERSAT concept is not advantageous! In spite of this particularity, it will be shown in the next part that the unit volume torque of SUPERSAT can be higher than that of conventional machines. The main reasons being the following:
- The filling factor of the iron free SUPERSAT armature is better, the shape of the design leads to an important volume of energy conversion.
- The iron plugs being saturated, their relative permeability is not far from unity: the whole working zone has an "iron free" behaviour when subjected to the field of armature windings.

These two circumstances allow the armature current of SUPERSAT to be quite higher than that of a conventional machine, leading to a large value of the unit volume torque.

Moreover, other particularities of the concept must be noticed:
- No moving coils, all the rotating parts are rigidly locked.
- Zero torque applied to the static superconducting coil.

III - MODELISATION - UNIT VOLUME TORQUE EXPRESSION

With the hypothesis described in the previous chapter, and assuming an armature modelisation where all the winding space is filled with copper, with a mean current density \( J_r \), \( J_M \), the variable flux density \( B(\theta) \) for \( R_1 < \rho < R_2 \) may be represented by a square-function. The first harmonic:

\[
B_1(\theta) = \frac{2}{\pi} \alpha \mu_0 M_s \cos \rho \theta
\]  

is used to calculate the torque when a sinusoidal distribution is assumed for current density:

\[
J_1(\theta) = K_r J_M \cos \left[ \rho (\theta + \xi) \right]
\]

In polar coordinates, the elementary torque on volume:

\[
d^2T = 2b (1 - \omega) \rho d\rho d\theta
\]

is given by the relation:

\[
d^2\Gamma (\rho, \theta) = \rho B_1(\theta) \times dI_1(\theta) \times d\rho
\]

where:

\[
dI_1(\theta) = 2b (1 - \omega) R_1 J_1(\theta) d\theta
\]

By integration of the relation (2.4), we obtain the unit volume torque:

\[
\frac{\Gamma}{V} = K_T \mu_0 M_s R_1 J_M \cos (\rho \xi)
\]
with:

\[ K_T = \frac{1}{\pi} \alpha (1 - \alpha) (1 - \frac{R_1}{R_2})^2 K_r. \]  \hspace{1cm} (2.7)

In relations (2.6) et (2.7)
- \( \alpha (1 - \alpha) \) is optimal for \( \alpha \) equal to 0.5
- Factor \( (1 - \frac{R_1^2}{R_2^2}) \) is limited by mechanical constraints and is smoothly varying for low values of \( \frac{R_1}{R_2} \) ratio. A realistic value of this ratio should be for example \( \frac{R_1}{R_2} \geq 0.5 \).
- The saturation induction \( (\mu_0 M_s) \) value lies, as known, between 2 and 2.4 Tesla.
- Maximum armature current density \( J_{M_a} \), is mainly depending on the cooling process.
- Copper filling rate \( K_r \) is function of phase to phase insulation and directly depending on the voltage level. For lowest voltages, a value \( K_r \) greater than 0.3 can be obtained.
- The \( \xi \) angle is related to the voltage and the power factor. The maximum of \( \frac{\Gamma}{V} \) is obtained when \( \xi = 0 \).

Assuming \( \xi = 0 \), the armature field can be written:

\[ H = (1 - \alpha) \frac{1}{\pi} R_1 K_r J_{M_a} \]  \hspace{1cm} (2.8)

We can then define ratio \( \beta \) between the inductive drop voltage modulus and the e.m.f.
From (2.1) and (2.8), we obtain:

\[ \beta = \frac{\pi}{2} \frac{1 - \alpha}{\alpha} K_r \frac{R_1 J_{M_a}}{M_s} \]  \hspace{1cm} (2.9)

At this step, two types of limitation appear, the first one is due to thermal constraints which limit the current density to \( J_1 \), the second one is relative to \( \beta \) ratio which cannot exceed limit value \( \beta_1 \).

From the relation (2.9) and \( \beta = \beta_1 \), a particular value of \( R_1 J_{M_a} \) could be deduced:

\[ R_1 J_{I_1} = \frac{2}{\pi} \frac{M_s}{K_r} \beta_1 \]  \hspace{1cm} (2.10)

For \( R_1 J_{I_1} < R_{10} J_{I_1} \) the only constraint is a thermal one. The absolute maximum unit volume torque (given by (2.6) with \( \xi = 0 \)) is linearly increasing with \( R_1 J_{I_1} \) product and does not depend on the number of pole pairs, \( \alpha \) being constant (\( \alpha 0.5 \)).

If \( R_1 > R_{10} \), the condition imposed on \( \beta (\beta = \beta_1) \) leads to an optimal value of \( \alpha \) that will be calculated from (2.9):

\[ \alpha = \frac{1}{1 + 2 \beta_1 M_s \beta} \]  \hspace{1cm} (2.11)

Thus, the optimal value of \( \alpha \) is now greater than 0.5 meaning that the thickness of the rotating discs is higher than that of the armature discs. Correlatively \( (\Delta B)_{max} \) increases.

The absolute maximum of \( \frac{\Gamma}{V} \) given by (2.6) becomes:

\[ \frac{\Gamma}{V}_{max} = 3 \mu_0 (K_r R_1 J_{I_1})^2 / [ \beta_1 \beta_1 (1 + 2 K_r (R_1 J_{I_1})) / (2 \beta_1 \beta_1 M_s) \]  \hspace{1cm} (2.12)

As an example, by taking \( \beta_1 = 0.5 \), \( \mu_0 M_s = 2.2T \) and \( K_r = 0.3 \), the curves of \( \frac{\Gamma}{V}_{max} \) in terms of \( R_1 J_{I_1} \) or \( p \) are reported in figures 2 and 3.

For a comparison, in figure 3, a typical \( \frac{\Gamma}{V} \) of classical a.c synchronous machine is plotted/4/ (\( \frac{\Gamma}{V} \))

![Graph](Fig. 2 - Unit volume torque versus \( R_1 J_{I_1} \) product)

![Graph](Fig. 3 - Unit volume torque versus number pole pairs \( p \) (dotted line for conventional salient poles a.c. machines)
Realistic values of \( R = 0.35 \text{m} \) and \( J_i = 0.20 \text{A/mm}^2 \) should give a \( \frac{\Omega}{V} \) value of 275 kN/m\(^2\) for \( p > 4 \).

As an example, table 1 gives the compared dimensions of a particular 44 MVA SUPERSAT design and the dimensions /5/ of a conventionnal machine:

<table>
<thead>
<tr>
<th>Conventional salient poles machines</th>
<th>SUPERSAT structure (10 armature discs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent power ( S_M = 44 \text{ MVA} )</td>
<td>( S_M = 44 \text{ MVA} )</td>
</tr>
<tr>
<td>Speed rotation ( N = 500 \text{ r.p.m} )</td>
<td>( N = 500 \text{ r.p.m} )</td>
</tr>
<tr>
<td>Pole pairs ( p = 6 )</td>
<td>( p = 6 )</td>
</tr>
<tr>
<td>Rotor diameter ( D_r = 3.70 \text{ m} )</td>
<td>( D_r = 1.40 \text{ m} )</td>
</tr>
<tr>
<td>Rotor length ( L_r = .78 \text{ m} )</td>
<td>( L_r = 1.98 \text{ m} )</td>
</tr>
<tr>
<td>Unit volume torque ( \frac{\Omega}{V} = 100 \text{ kN/m}^2 )</td>
<td>( \frac{\Omega}{V} = 275 \text{ kN/m}^2 )</td>
</tr>
</tbody>
</table>

**TABLE 1**

**IV - EXPERIMENTAL PROTOTYPE SUPERSAT 01**

An experimental program is now under development in G.R.E.E.N. Laboratory in association with C.E.A. SACLAY. A first prototype using a single armature disc of diameter 30 cm and two polar wheels with \( p = 8 \) is under construction.

The experiments will deal with field distribution and measurements of the electrical parameters of the machine. The maximum performance being directly dependent on the armature current density \( J_i \), further developments will include high performance cooling of the armature disc.

**V - CONCLUSION**

The SUPERSAT concept applied to a.c machines with a high number of poles, presents several interesting features:
- A solid iron rotor without windings;
- A torque free superconducting fixed coil;
- An iron free, easy to cool armature winding.

The expected high values of unit volume torque would allow SUPERSAT to compete favourably with the classical salient poles machines, in the range of high power, low speed applications.

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