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PREPOLARIZED INDUCTANCES FOR CERN

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RESUME - Le LEP (Large Electron Positron collider), étudié par le CERN et en cours de construction près de Genève, est un anneau dans lequel des faisceaux de particules circuleront dans les années 90. Afin de contrôler la trajectoire de ces particules, des électroaimants pilotés par des alimentations courant continu très précises sont requis, la puissance de ces dernières allant de quelques KW à plusieurs MW.

Afin de répondre aux spécifications des alimentations de 20 à 80 KW, plusieurs solutions ont été étudiées/1/. Une d'entre elles est un hacheur constitué de 2, 3 ou 4 modules 75A/250V mis en parallèle, et qui utilisent quelques principes originaux et particularités technologiques : Contrôleur de courant à pente négative, aides à la commutation sans pertes, inductances de lissage prépolarisées/2/. Ce dernier point a permis une réduction importante de la taille des modules. Nous donnons dans ce papier le principe du calcul de ces inductances et l'utilisation qui en est faite dans cette application.

ABSTRACT - The LEP (Large Electron Positron collider), studied and actually being built near Geneva, is a ring in which beams of particles will circulate in the 90's. In order to control the path of these particles, electro magnets, driven by very precisely controlled DC supplies are required, the output power of the latter ranging from a few KW to several MW. To fulfill the specs of the 20 to 80 KW supply, several solutions are being studied/1/. One of these solutions is a chopper built up with 2, 3 or 4 75A/250V modules in parallel, which use some original principles and technological peculiarities : Slope compensated current controller, snubbers without loss, prepolarized smoothing chokes/2/. This latter point allowed an important reduction of the size of the modules. The principles for the calculation of these inductances and their use in this application are given in this paper.

I - INTRODUCTION -

The considered converter is a chopper at 16 kHz (fig.1) which works as follows :

![Fig. 1: Single chopper](image1)

![Fig. 2: Double chopper](image2)

The set up is supplied by the 380V three phase mains through a transformer (T) and a rectifier bridge (R). A first cell (L1+C1) has a double function : To smooth the 300 Hz (the rectified 3 phase 50 Hz) and to prevent the pollution of the mains by the switching frequency (16 kHz) its harmonics. The cell L2+C2 is there mainly for the smoothing of the output. During phase "on" of the power transistor (Tr), the mains feeds the load (EM:electromagnet) through L2+C2. The diode (D) is "off". In the phase "off" of Tr, D is "on" and L2+C2 restores a part of the accumulated energy to the load. In that configuration (single chopper), the 50 Hz transformer is a choice to have one terminal of the load grounded. In the case of the double chopper, the load is not grounded (fig. 2).

In both cases (single and double choppers), the current through the inductances is the sum of a direct current (Io) and a superimposed periodic current at 16 kHz.
the amplitude of this latter ($\Delta I$) being smaller than $I_0$. This leads to the fact that the smoothing chokes are generally larger, to prevent saturation by $I_0$, than required to insure the correct impedance ($L.2f$) for the alternating component (fig. 3a). The superposition of a magnetic flux, opposite to that created by $I_0$ shifts the rest point of the inductance (fig. 3b). This reverse flux can be obtained by means of a direct current, which is not very interesting, or with a permanent magnet set in the airgap of the core, which is more clever (that airgap exists in smoothing chokes, in order to prevent saturation). As the permeability of the magnet is the same as that of the air, the dynamic characteristics of the core are unchanged. So, it is possible : With the same core to allow a larger $I_0$ (fig. 3b); or for the same $I_0$ and $\Delta I$ to use a smaller core (fig. 3c).

By means of prepolarization, important gains can be expected on core volume, winding, and therefore costs/2/.

**II – THEORY –**

In this chapter, the indexes $f$, $m$ and $a$ refer to the ferrite, magnet and airgap respectively.

Let us consider: a ferrite core (permeability $\mu_1$, cross section $S_f$, electric length $\lambda$) with an airgap (length $\epsilon$) (fig. 4); inside the gap, a magnet (cross section $S_m$, length $\epsilon_m$, magnetization $J_m$, maximum reverse field before demagnetization $H_k$) (fig. 5a, 5b); and a N turns winding. Let $\beta = S_a/S_f$, $S_a$ being the effective cross section of the flux inside the gap. Because of the leakage : $\beta > 1$.

**Fig. 4 : Core with magnet**

**Fig. 5a : Ferrite**

**Fig. 5b : Magnet**

### II-1- The following hypothesis are made:

1) The gap is important and the effective permeability of the core ($\mu_2$) is less than 5% of $\mu_1$, the reluctance of the ferrite circuit is negligible compared to that of the gap:

$$\frac{1}{\mu_2}, \frac{1}{S_f} < \epsilon \frac{c}{S_a}$$

or $\rho \approx \frac{B_2}{c}$ (1)

2) The permeability of the magnet is $\mu_m = 1$, the losses are negligible (small volume, high resistivity).

3) The magnet is not demagnetized during the operation: $J = J_m$.

4) The core is not saturated, i.e. the induction in the ferrite ($B_f$) remains less than the limit $B_n$ (fig. 5a).

**II-2- With that set of hypothesis, the induction in the ferrite ($B_f$) and the field in the magnet ($H_m$) are obtained by the superposition of the two following cases:**

- the core with a current, without magnet ($B', H'$) and core with a magnet, without current ($B'', H''$).
Core without magnet, \( I \neq 0 \): From the circulation of the field and from hyp.1 we have: \( NI = H'_a \varepsilon \); the induction in the gap gives: \( B'_g = H'_a \varepsilon \); and the conservation of the flux at the interface (ferrite/gap): \( B'_f = 0 \). We derive from these relations:

\[
B'_f = B\mu_0 \frac{NI}{\varepsilon} \quad (2)
\]

Core with magnet, \( I = 0 \): The circulation of the field and hyp. 1 give:

\[
(c - \varepsilon_m) H''_a - \varepsilon_m H''_m = 0; \quad \text{as the permeability of the magnet is 1, we have:}
\]

\[
B''_a = \omega H''_a = B''_m; \quad \text{the point of operation of the magnet gives:}
\]

\[
B''_m = J_m - \varepsilon \mu_0 H''_m,
\]

and the conservation of the flux gives: \( B''_m S_m = B'_f S_f \). From these relations we derive \( B''_f \) and \( H''_m \):

\[
B''_f = \frac{c m}{\varepsilon} \cdot \frac{S_m}{S_f} \cdot J_m \quad \text{and} \quad H''_m = \frac{1}{\mu_0} \cdot \frac{c - cm}{\varepsilon} \cdot J_m
\]

\[ \quad (3) \]

\[ \quad (4) \]

II-3- We derive the higher currents before saturation from these relations, in both cases (with and without prepolarization):

\[
(2) \quad \text{gives:} \quad I_{\text{max}} = \frac{1}{\mu_0 N} \frac{c}{\beta} B_{f, f} \quad (5) \quad \text{without magnet}
\]

\[
(3) \quad \text{gives:} \quad I_{\text{max}} = \frac{1}{\mu_0} \frac{c}{\beta} \left[ B_{f, f} + \frac{c m}{\varepsilon} \cdot \frac{S_m}{S_f} \cdot J_m \right] \quad (6) \quad \text{with magnet}
\]

The "improvement factor" is defined as \( k = I_{\text{max}}/I_{\text{max}} \)

\[
k = 1 + \frac{c m}{\varepsilon} \cdot \frac{S_m}{S_f} \cdot J_m \quad (7)
\]

II-4- The maximum allowed current \( I_{\text{dem}} \) before the demagnetization of the magnet (irreversible operation), is the value for which the field \( H_m \) reaches the knee of the B-H curve (fig. 5): \( H_m = H_k \). Relation (4) then gives:

\[
I_{\text{dem}} = \frac{c}{N} \left( H_k - \frac{1}{\mu_0} \frac{c - cm}{\varepsilon} \cdot J_m \right)
\]

\[ \quad (8) \]

In order to have a reversible operation of the prepolarized core, the relation \( I_{\text{dem}} > I_{\text{max}} \) must be fulfilled. From (1), (6) and (8), this condition reads:

\[
\frac{1}{\mu_0} \frac{c}{\varepsilon} \cdot \frac{S_m}{S_f} \cdot \frac{J_m}{B_{f, f}} > \frac{c - cm}{\varepsilon} \cdot J_m
\]

\[ \quad (9) \]

If (9) is fulfilled and if the magnet is in the flux guided by the ferrite, the magnet is protected from demagnetization by the saturation of the ferrite. From (9) a minimum thickness of the magnet can be derived.

Two important points are directly derived from these relations:

II-5-1- The prepolarization to the optimum i.e. so that \( B_f (I = 0) = - B_{f, f} \) and \( I_{\text{max}} \approx 2 \). \( I_{\text{max}} \), is obtained when (from (6)):

\[
\varepsilon_m S_m J_m = \varepsilon S_f B_{f, f}
\]

\[ \quad (10) \]

II-5-2- The prepolarization with a hard ferrite magnet (Ba or Sr Fe\(_{12}O_{19}\)): The magnetization \( J_m \) of that type of magnet is roughly equal to the limit induction before saturation of the ferrite \( (B_{f, f}) \). Relation (10) indicates that such magnet prepolarizes the core to the optimum, when it fills the gap \( (S_m = S_f, \varepsilon_m = \varepsilon) \). This latter point is important, for hard ferrite magnets are cheaper and more resistive (hyp.2) than rare earth magnets are.
One last point to be discussed is the position of the winding with respect to the magnet. In the case described in 11-5, we have $J_m = B_{fl}$, $\kappa = \kappa_f$, $S_m = S_f$. The condition for safe operation (non-demagnetization) becomes, from (9) and (1):

$$\beta > 2 \frac{B_{fl}}{\mu_0 H_k}.$$  

As for hexaferrite $B_{fl} = \mu_0 H_k$, this condition reads $\beta > 2$.

Experiments show that for a core with a ferrite magnet, this condition is not fulfilled if the magnet is inside the winding (for this latter reduces the effective cross section $S$ and $\beta$); a magnet with a higher $J_m$ is required (i.e. a plasto-samarium magnet). But if the gap and the magnet are outside the winding, the $\beta > 2$ condition is generally fulfilled.

All these points were applied to the inductances for CERN, that are described hereunder.

**III - EXPERIMENTAL -**

Two or four prepolarized inductances are required for each single or double module. Their characteristics are summarized in the next table. The $\beta$, $I_{\text{maxm}}$, $k$ and $I_{\text{dem}}$ values were derived from relations (1), (6), (7) and (8), assuming that the gap is completely filled by the hard ferrite magnet (with $J_m = 360$ T, $H_k = 250$ KA/m) and that $B_{fl}$ of B50 ferrinox is .300 T.

<table>
<thead>
<tr>
<th></th>
<th>SINGLE CHOPPER</th>
<th>DOUBLE CHOPPER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance value</td>
<td>$L_1 = 200$ μH</td>
<td>$L_2 = 190$ μH</td>
</tr>
<tr>
<td>$L_1$</td>
<td>67 A</td>
<td>91 A</td>
</tr>
<tr>
<td>Core size (mm$^3$)</td>
<td>2x(94x104x30)</td>
<td>141x156x45</td>
</tr>
<tr>
<td>$N$ turns, $r$ (mm)</td>
<td>15, 7</td>
<td>15, 8</td>
</tr>
<tr>
<td>$\beta$ (1)</td>
<td>2.7</td>
<td>2.6</td>
</tr>
<tr>
<td>$I_{\text{maxm}}$ (6)</td>
<td>90 A</td>
<td>108 A</td>
</tr>
<tr>
<td>$k$ (7)</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>$I_{\text{dem}}$ (8)</td>
<td>120 A</td>
<td>136 A</td>
</tr>
<tr>
<td></td>
<td>55 A</td>
<td>91 A</td>
</tr>
<tr>
<td></td>
<td>94x104x30</td>
<td>141x156x45</td>
</tr>
<tr>
<td></td>
<td>17, 7</td>
<td>14, 8</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>68 A</td>
<td>115 A</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>105 A</td>
<td>146 A</td>
</tr>
</tbody>
</table>

As an example, the curve $L_2$ (single chopper) versus $NI$ is given in fig. 6. It can be noticed that the core is slightly presaturated, which is consistent with $k=2.2$. The volume of this core, and the number of copper turns were reduced by 30% and 50% respectively, compared with a non prepolarized inductance having the same magnetic characteristics.

IV - CONCLUSION -

This reduction of the size of the inductances contributed to that of the supplies. Each 20 KW/80A/250V module could be packed in a 135 liter rack, allowing 5 modules (i.e. 100 KW) to be assembled in a standard 19’ x 2m mounting rack.

REFERENCES -