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DESIGN, MANUFACTURE AND TESTING OF THE SATURABLE INDUCTORS FOR JET OHMIC HEATING SUB-SYSTEM

T. Eriksson, A. Stella, K. Papp* and P. Tiez**

JET Joint Undertaking, U.K.
*Spesielektro Baslinger KG, 4020 Linz, Austria
**Ansaldo, Italy

Résumé — La coupure d'un courant continu nécessite un zero artificiel produit par un circuit de commutation LC dans le disjoncteur. L'utilisation d'une inductance saturable permet de maintenir le courant au voisinage de zéro pendant la commutation.

Cet article décrit la conception, la fabrication et les tests des Inductances Saturables destinées au Tokamak expérimental JET où les conditions maximales de fonctionnement normal sont 30 kV et 80 kA, et où le courant de défaut peut atteindre 180 kA.

Abstract — The interruption of a DC current requires an artificial zero to be produced in a circuit breaker by an LC commutation circuit. In order to prolong the phase of near zero current a saturable inductor can be suitably employed.

This paper describes the design, manufacture and testing of the Saturable Inductors required for the JET Tokamak Fusion Experiment where the normal operating limit is up to 30 kV and 80 kA and fault currents can reach 180 kA.

1. INTRODUCTION — Starting from the commutating circuit suggested during the JET design phase /1/, the detailed design requirements for the Saturable Inductors were identified after an extensive computer analysis of the overall circuit behaviour. The specification was drawn up with a large range of air gap and tap variations to cover every working condition of the JET machine.

The design adopted employs 24 air cooled coils arranged around a clock spring wound iron core in a toroidal configuration, which gives a very sharp transition from saturated to unsaturated condition and no stray field in the region outside the inductor. The manufacturing technology required for the coil impregnation and the general assembly is also described in the paper.

The test specification pays particular attention to the verification of temperature rise for pulsed loading as well as measurement of differential inductance. The results of the peak current test, requiring the use of a high power test station, as well as other major tests carried out to verify the performance characteristics of the inductor, are reported.

2. REQUIREMENT SPECIFICATION AND DUTY — A tokamak machine requires high voltage to be applied across the poloidal coils (fast change of magnetic flux) to ionise the hydrogen gas and produce a plasma current. This is achieved on JET by breaking a well established premagnetization current through the poloidal coils, and diverting it into parallel resistor branches /2/.

Air blast circuit breakers were found to be favourable for the breaking duty /3/ but in spite of a low jitter in the circuit breaker operation (± 0.15 ms), a substantial LC circuit proved to be necessary to commutate the current from the breaker at the time of interruption. With a capacitor bank of 1.2 mF charged up to 25 kV an inductance of 0.5 mH is required to interrupt currents up to 80 kA DC.

The most workable definition of inductance was found to be the use of differential inductance $L_d = d\psi/di$ (where $\psi$ is flux linkage) specified at maximum operating current and at zero current. The definition of the saturation point as the intersection of the air gap characteristic and the iron saturation asymptote completes the inductance specification. In order to cope with circuit performance requirements within a wide range, a great deal of flexibility was specified.

The most severe mechanical and thermal requirements are set by the short circuit current of 180 kA with $L^2 t = 3.6 \times 10^{10}$ A²s. No steady state load was specified but a pulsed current of 80 kA with an $L^2 t = 10^{10}$ A²s every 10 minutes, up to $10^5$ times, which has also required the design to be looked at from a mechanical fatigue point of view. A 30 kV insulation voltage between terminals and to earth was specified for normal operation.
3. DESIGN — The main design requirements for the Saturable Inductor can be summarized as follows:

a — No magnetic field leakage at the inductor vicinity, to avoid undesirable effects, such as forces on busbars and electric interference to electronic components nearby.

b — Sharp-edged magnetic characteristic, i.e. sharp transition from saturated to unsaturated condition.

c — Features for adjustment, i.e. adjustable inductance and adjustable saturation current.

The above requirements are met by:

a — Toroidal winding configuration.

b — Toroidal core arrangement, with short air gaps, compared to the length of the core.

c — Variable number of turns and adjustable thickness of air gaps.

A general layout of the inductor is shown in Fig.1. The winding consists of 24 parallel connected disc coils of 14.2 turns, arranged in a toroidal configuration around an annular iron core. Each coil is wound with aluminium conductor of 30 mm x 3.7 mm cross section prewrapped with nomex and fibreglass tape insulation, and impregnated under vacuum with epoxy compound to increase dielectric and mechanical strength. Nomex and fibreglass tapes on the conductor are interleaved, as shown in Fig.2 enabling the epoxy to penetrate into the insulation, bonding the conductor surface and preventing interturn conductors from sliding. Five taps are provided in the upper region of each coil for manually setting the number of turns.

The coil terminals consist of a flexible cable at the tapped coil end and a rigid rod at the other. They are connected to circular busbars located around the toroidal winding, and to the main terminals. The mechanical structure, designed to keep the forces on the winding, consists of two co-axial fibreglass cylinders arranged inside and outside the winding and 2 x 24 fibreglass wedges acting as spacers between individual coils, arranged above and below the fibreglass cylinders and compressed by non-magnetic steel bolts.

The clock-spring wound core, manufactured with 0.3 mm thick grain oriented iron is vacuum impregnated in epoxy resin. Variable air gap setting is provided by four laminated iron wedges, located symmetrically along the annular core (Fig.3). An overall air gap adjustment, ranging between 4 and 26 mm can be obtained by sliding the wedges in a radial direction.

Cooling requirements are met by forced air flow, driven by a fan located below the winding. The air flow is guided across the winding by a case of glass-reinforced polyester resin, which completely encloses the inductor. Ohmic heating of the winding is the major heat load during pulsed operation, eddy current heating the winding and of the iron core is negligible. The adiabatic temperature rise of the conductors per pulse operation at rated I²t was calculated to be 21.5°K the mean temperature rise at thermal steady state and rated load cycle was estimated to be 63.5°K. All insulating components used correspond to temperature class F. An insulation level of 95 kV (lightning impulse to earth) is achieved by post insulators. The main parameters of the inductor are summarised in Table I:
Table I: Major Inductor Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Inductance (Unsaturated)</td>
<td>500 µH</td>
</tr>
<tr>
<td>Nominal Inductance (Saturated)</td>
<td>12.4 µH</td>
</tr>
<tr>
<td>Winding Resistance (20°C)</td>
<td>400 mΩ</td>
</tr>
<tr>
<td>Nominal Saturation Current</td>
<td>2 kA</td>
</tr>
<tr>
<td>Range of Saturation Current</td>
<td>1 to 4 kA</td>
</tr>
<tr>
<td>Nominal peak current</td>
<td>80 kA</td>
</tr>
<tr>
<td>Maximum peak current</td>
<td>180 kA</td>
</tr>
<tr>
<td>Nominal thermal rating</td>
<td>$10^{10}$ A²/s</td>
</tr>
<tr>
<td>Maximum thermal rating</td>
<td>$3.6 \times 10^{10}$ A²/s</td>
</tr>
<tr>
<td>Class of Insulation</td>
<td>F</td>
</tr>
<tr>
<td>Type of cooling</td>
<td>Air forced</td>
</tr>
<tr>
<td>Lamination - Grain oriented iron</td>
<td>30 M5</td>
</tr>
<tr>
<td>Thickness of lamination</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Impulse voltage to earth</td>
<td>95 kV</td>
</tr>
<tr>
<td>Impulse voltage across terminals</td>
<td>60 kV</td>
</tr>
</tbody>
</table>

4. TESTING — Tests have always proved to be a useful guideline for the manufacturer and the most straightforward way to identify problems early enough to solve them. The Saturable Inductors were then subjected to tests according to IEC Standard/Recommendations, whenever applicable, and to additional tests to prove the required performance and duty.

4.1 Peak Current Test — Aim of the test was to prove the withstand capability as well as to study the effect of the sharp transition from saturated to unsaturated conditions. The test was performed at KEMA test station by applying a fully asymmetrical AC current for 20 ms (Fig.4). The inductor always remains in a saturated condition (12.4 mH) except for the narrow range around zero ($\pm 2$ kA) when almost all the generator voltage drops across the unsaturated inductor (500 mH).

4.2 Differential Inductance Measurements — The Saturable Inductor is a key component of the commutation circuit and the knowledge of the parameters concerned is an essential piece of information to optimize the current breaking operation.

The usual measuring methods, suggested in the literature were found impracticable so that a new method was implemented (Fig.5). The two identical Saturable Inductors under tests are arranged as two branches of a bridge, the other two branches being identical capacitors. The inductors are polarized by a DC current, establishing a well defined point along the $\psi$–I characteristic. An AC generator is used to provide a comparatively small current superimposed on the DC current. The measurement of the AC current at the generator output and the AC voltage component across an inductor gives the differential inductance $L_d = d\psi/di$, as a function of the polarization current (Fig.6), on the assumption that the two branches of the bridge are identical. The $\psi$–I characteristic, obtained by integrating the differential inductance, is also given in Fig.6. One of the advantages of the method is that, provided generator frequency and bridge capacitance are properly chosen, the measurement is very marginally affected by the ripple voltage and current produced by the rectifiers. The values of differential inductance, measured for every setting of turns, are shown in Table II:

Table II: Inductances in µH at nominal air gap

<table>
<thead>
<tr>
<th>Turn number</th>
<th>Unsaturated</th>
<th>Saturated</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-2</td>
<td>230</td>
<td>5-6</td>
</tr>
<tr>
<td>9-2</td>
<td>305</td>
<td>7-5</td>
</tr>
<tr>
<td>10-2</td>
<td>480</td>
<td>12-5</td>
</tr>
<tr>
<td>12-2</td>
<td>690</td>
<td>18-8</td>
</tr>
<tr>
<td>14-2</td>
<td>940</td>
<td>27</td>
</tr>
</tbody>
</table>

4.3 Temperature Rise Test — The main aim of the test was to ascertain that the maximum temperature did not exceed the limits allowed by the insulation class, i.e. 100°C over temperature under normal duty, and 200°C in fault conditions. The test was also intended to provide information
on the thermal behaviour in any other load conditions. It should be noted that the adiabatic temperature rise, for a given $P t$, and the consequent decay (i.e. the step response) are sufficient to predict the thermal behaviour under every load condition, in a range where the effect of the resistance rise with the temperature can be neglected. First the winding at maximum tap, were subjected to the equivalent continuous rating (4.1 kA), until thermal steady state conditions were achieved ($\theta_2$ in Fig.7a). Then a quasi adiabatic rise $\theta_2 - \theta_1$ (cooling fan switched off) was produced by applying a thermal load of $10^{16}$ $A^2 s$. Finally, with the fan switched on, the system was left to decay for 600 s to $\theta_3$. The winding temperatures were measured during the test by resistance measurement, according to IEC 289, with a 3 A current injected into the coils. Two measurements of the DC voltage drop across the terminals of the inductor were carried out, with opposite current, to suppress errors due to the thermocouples at the copper/aluminium interface. From the measured temperatures the normal duty cycle is immediately found from (Fig.7b)

\[
\begin{align*}
\theta_3 &= \theta_2 \cdot \phi(t) \\
\theta_{\text{min}} &= \theta_{\text{max}} \cdot \phi(t) \\
\theta_{\text{max}} - \theta_{\text{min}} &= \theta_2 - \theta_1 \\
\theta_{\text{max}} &= \theta_2 \cdot (\theta_2 - \theta_1)/(\theta_2 - \theta_3) \\
\theta_{\text{min}} &= \theta_3 \cdot (\theta_2 - \theta_1)/(\theta_2 - \theta_3)
\end{align*}
\]

with the only assumption that the temperature decay can be expressed in the form $\theta = \theta_0 \cdot \phi(t)$. The two conditions, set in the specifications, $\theta_{\text{max}} \leq 100^\circ C$ in normal duty and $\theta = \theta_{\text{min}} + 3 \cdot 6 \times (\theta_2 - \theta_1) + 40 \leq 200^\circ C$ in fault conditions proved to be satisfied.

5. CONCLUSIONS – The Saturable Inductors are currently being used in JET operation as a part of the Ohmic Heating Circuit. Currents up to 120 kA have been passed through and interruptions up to 40 kA have been successfully performed so far. Artificial zero of current, lasting ~1 ms, and inductor behaviour proved to be well in agreement with analytic and numerical predictions, so that operation to full design performance is expected to be comfortably achieved.

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/3/ Dokopoulos (P), Kriechbaum (K), Elektrotechnische Seitschrift, 1976, H8, 499.