A Device for Measuring High Current at Cryogenic Temperatures

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Abstract-- **In order to measure high current (several tens of kilo Ampere) at low temperature (down to 4.2K), we have developed collaboration with Hitec Power Protection (Netherlands ex. Holec). This company sell the Macc+ (a low cost Direct Current Control Transformer) which measures up to 600A (AC and DC) at 300K. Several limitations of the standard Macc+ will be pointed to find the adapted solutions for the different users conditions (temperature, current level and background magnetic field). With some minor modifications to the standard produce, we could place the torus sensor at low temperature (the electronic is still at 300K) and we measured up to 3kA in liquid helium at low field. Analysis of the behavior of the device in non-standard conditions and experimental results will be reported. With more modifications, we could measure up to 38kA at 4.2K in a 0.5T-background magnetic field.**

Index Terms—**Direct Current Control Transducter, DCCT, High current measurement, mumetal at cryogenic temperature, zero-flux transformer.**

I. INTRODUCTION

USUALLY superconductors at 4.2K are carrying current created by power supply working at room temperature. But to generate very high current, without having huge facility, low temperature power supply can be designed especially with a transformer. In this case, high current at low temperature must be measured. To reach this purpose, in collaboration with Hitec Power Protection, we developed a Direct Current Control Transformer, DCCT, which the measuring head is working at liquid helium temperature. This device is part of our high current facility at Saclay which reached 70kA [1].

A. Principe of measurement for a DCCT

The DCCT consists of a measuring head and an electronics module. The conductor which carries the current to be measured forms the primary winding. The magnetic circuit is constituted by a set of 3 ferromagnetic toroidal cores (mumetal) fitted with a common secondary winding (Ns) and separate auxiliary windings (Na), all integrated in the measuring head (Fig.1). The principle of measurement is based on obtaining a perfect balance between the magnetic flux generated by the current in the primary current carrier and that generated by the current in the secondary winding. This balance point is known as the zero flux condition.

Any change of current in the primary winding causes a change of flux through the toroids, which in turn induces a voltage in the auxiliary windings. The voltage of Tf (“f” as flux) is fed to the power amplifier and the resulting current enters the secondary winding, where an equal but opposing flux is produced to counteract the original change of flux. The secondary current is then directly related to the primary current by the turns ratio of the primary winding to the secondary winding.

To minimize the effect of drift, the zero-flux current transformer is furnished with a magnetic modulator. The auxiliary winding wound around toroid Te (“e” as excitation) is excited by a rectangular voltage of fixed frequency generated by an oscillator. To compensate for the voltages induced in the primary current carrier and the secondary winding, a third toroid Tc (“c” as canceling the excitation), is placed in symmetrical position form Tf with opposite current. At the condition of zero flux, the magnetizing current in the excitation winding exhibits halfwave symmetry (Fig.2). To prevent any hysteresis occurring due to remanent magnetization, the magnetizing currents is adjusted to saturate toroid Te and Tc. When there are asymmetrical signals, the average value of the output voltage of the asymmetry detector gives a signal to the power amplifier in order to decrease the toroid saturation and coming back to zero flux condition.

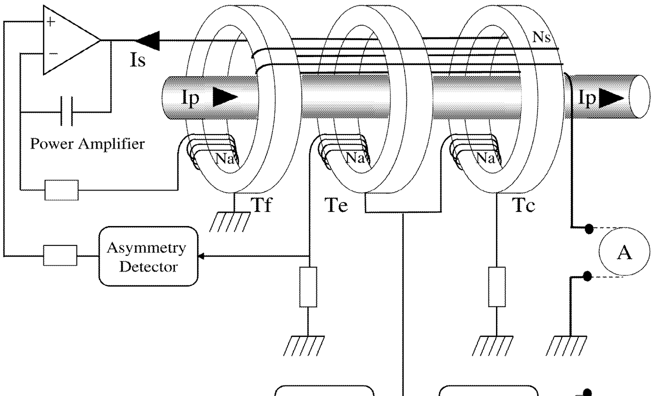

Fig. 1. Macc+ principle scheme.

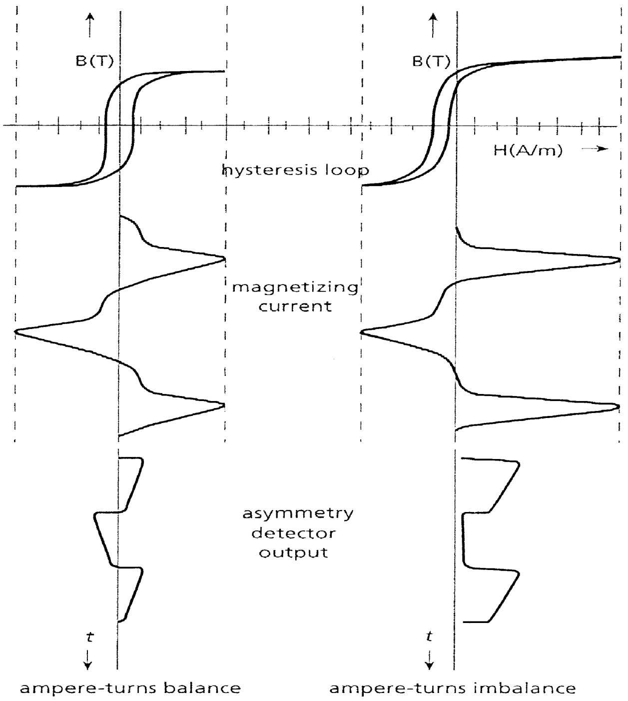

Fig. 2. Principle of the magnetic modulator

TABLE I
MACC+ CHARACTERISTICS

Specification	Values
Rated current (Ip)	600A
Over current	1 000A (10s)
Short-circuit current	3 000A (0.1s)
Current transformer ratio	1 000 : 1
Supply voltage / current	±15V / ±625mA
Hole of the measuring head	Ø=43mm
Noise 0 - 50kHz	$< 2\ 10^{-6}$
DC accuracy	$\sim 10^{-5}$
Output valid signal $\Delta I/I$	$< 10^{-3}$ (Ip=0)

TABLE II
MODIFICATIONS TO INCREASE THE EXCITATION CURRENT

Resistance name written on support	Initial values (Ω)	Added values (Ω)	Resulting values (Ω)
R1	~10	10	~5
R15	10	10	5
R14	1.5k	1k	600
R19	182k	150k	82k

B. *Performances of the standard Macc+*

The main performances of the standard Macc+ are resumed in Table I.

A signal call “output valid” is indicating if the measurement is correct. In the worst case (secondary circuit voluntary open), the signal detects a primary current of 0.6A. Precision of the output valid signal will increase with some local saturation of the mumetal torus when high current is measured.

II. TEMPERATURE INFLUENCE AND OTHER LIMITATIONS

A. *Introduction*

Only the measuring head has to be at low temperature. We add long cables between the electronic module and the measuring head that is placed inside the cryostat at low temperature. We use 3 shielded cables of 5 m long: one big for the secondary current, the second for the flux signal and the third for the excitation and the excitation canceling. We observe an offset corresponding to $5\ \mu A$ and the noise increasing up to $\pm 10\ \mu A$.

B. *Mumetal torus*

When we cool down the measuring head with the mumetal torus at nitrogen temperature, the device was not working any more. In fact, the excitation current was not strong enough any longer to produce mumetal torus saturation. We increase the excitation current by a factor of 4 to reach completely the saturation and to have maximum level of signal at the asymmetry detector. More precisely, we modified 4 resistance values by placing 4 resistances in parallel according to Table II.

For an excitation current of 18.5mA, we measured the hysteresis cycle at 300K and 4.2K without primary current. (Fig.3). The cycle at 77K is nearly the same that as 4.2K. We used the following data to reach the standard units : 200 turns with a section of 20.3mm^2 for mumetal and an average diameter of 50.5mm. At 300K, we find only 0.5T at 20A/m instead of expected 0.65T for mumetal. H_c is between 2 and 4A/m instead of the expected 1.5A/m. This should correspond to a stress about 10 N/mm^2 due to thermal contraction between mumetal and PbSn soldering [2].

Because of the coercive field, the cycle is not completely symmetrical. The coercive field increases by a factor of 2 at low temperature, therefore the Macc+ precision decreases also about a factor of 2.

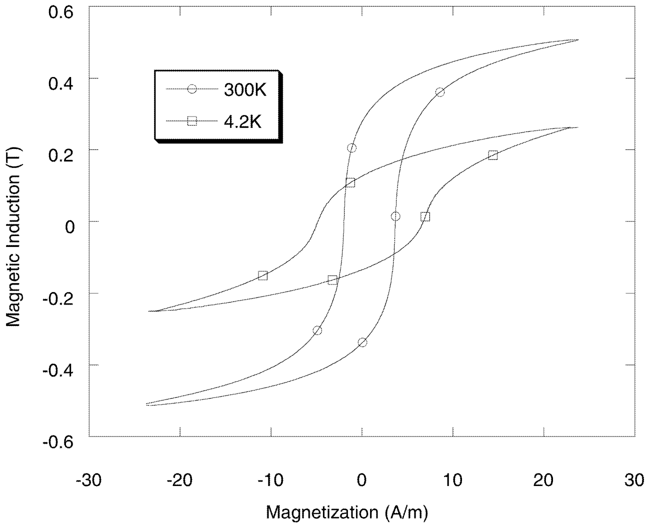

Fig. 3.: Mumetal torus magnetization as a function of applied field at two different temperatures.

C. *Limitation of the Macc+*

With an excitation current of 18.5mA, we have a device that is working from room temperature to 4.2K. The limitations of this device are the following:

- the compensating current is limited to 1.1A with the measuring head connected (1 100At).

- The conductor to be measured must be well centered and if possible round to avoid local mumetal saturation due to its self magnetic field induction. e.g. we made a test with a Rutherford cable (25mm×2.3mm) which get output valid information wrong (mumetal saturation) at 8kA.

- The external field should be lower than 0.1T to avoid mumetal saturation (c. f. Fig.3)

- The 1000 turns compensating winding is a copper wire of 0.4 mm diameter (with good cooling at 4.2K, we can expecte a maximum of 10 A which will produce about 10 W which evaporated helium, that means 10kAt).

III. OVER PASSING THE LIMITATIONS

A. *How to increase the compensating current?*

We used the same principle of power amplification to increase the current from 0.6A to 20 A with the following scheme (Fig.4). This power amplifier is out of the Macc+ box. Tree wires are connected from the new power transistors to the Macc plus : two to the Darlington transistor pins (emitter) which must be disconnected from ±15 V and one to the collectors. There are also 2 wires to the power supply and one for the secondary current (Is).

For all other limitations to be exceeding, the measurement head must be modified.

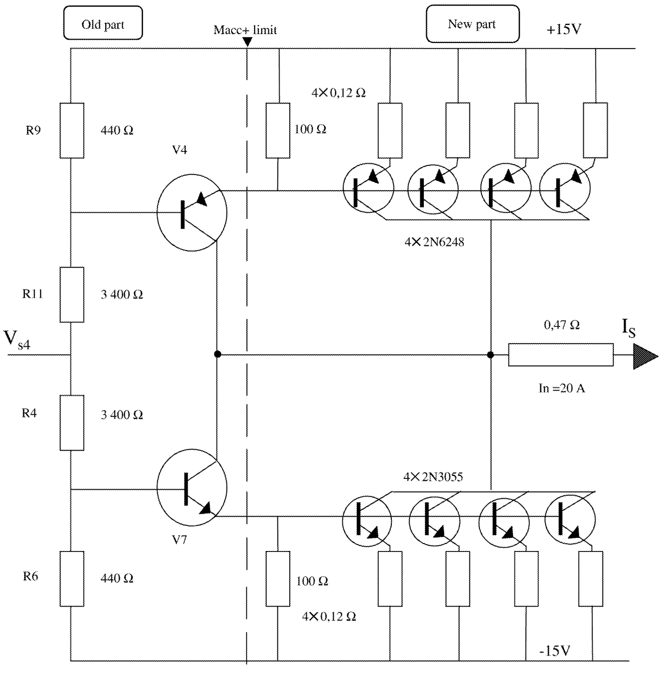

Fig. 4. New power amplifier level.

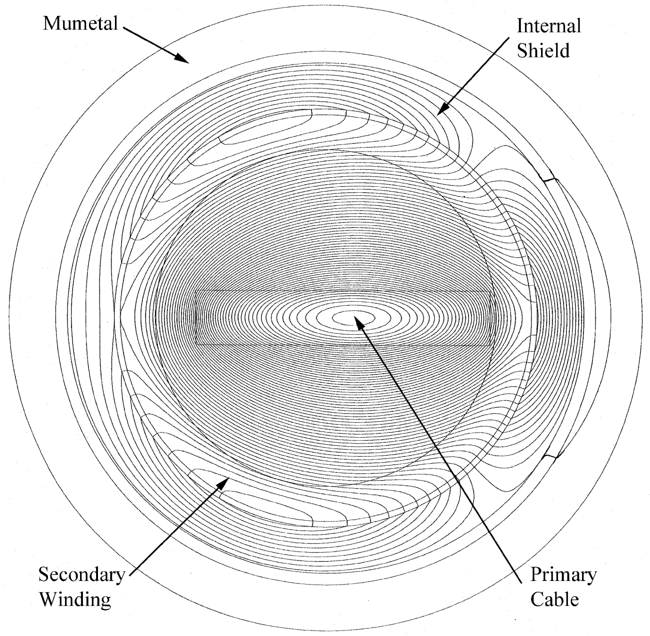

Fig. 5. Flux lines of the internal shielded mumetal torus. This case correspond to Rutherford cable of 4.6 mm × 25 mm mis-centered of 1.5 mm with 4 mm think internal shield. The primary current is 100 kA. The auxiliary current and the secondary external return are not plotted. The internal shielding reduced the maximum field inside the mumetal (70 mT) by a factor of 20. Courtesy of F.P.Juster

B. *How to limit the mumetal saturation?*

There are two sources of possible saturation, the field of the conductor to be measured and the external field. The solution principle consists to shield all around the mumetal torus inside the secondary winding.

1) *Conductor self magnetic field*

If the current gravity center is not centered or the current distribution is not of revolution inside the torus, localized saturation occurs inside the mumetal. The current repartition between cable strands can be not uniform due to end limit effects except near the critical current were strand performances are limiting and with same critical current for all strands, the uniform repartition is reached.

By placing an internal iron ring, we can reduce both effects (Fig.5). The shield dimensions depend of the available space. The gap between the shield and the mumetal can be reduced to the minimum including auxiliary winding and the mounting space: the shield thickness is more efficient than space between shield and mumetal. We use 3.5mm for the internal shield that lead to 30mm diameter for the hole with 10 000 turns of wire Ø = 0.224 mm.

2) *External magnetic field*

The external field is shielded by an external magnetic torus ($Ø_i$ = 58 mm and $Ø_{ex}$ = 79 mm) and two flanges placed at both sides (8 mm thick). Indeed the 3 torus are closed in the shielded box with only three 1 mm diameter holes for the 3 auxiliary windings. This shielding is designed to be compatible with a stray field of 0.5 T. A cross section presents the 4 shielding elements (Fig.6). The shield is made with 0.1 mm thick FeSi oriented grain tape.

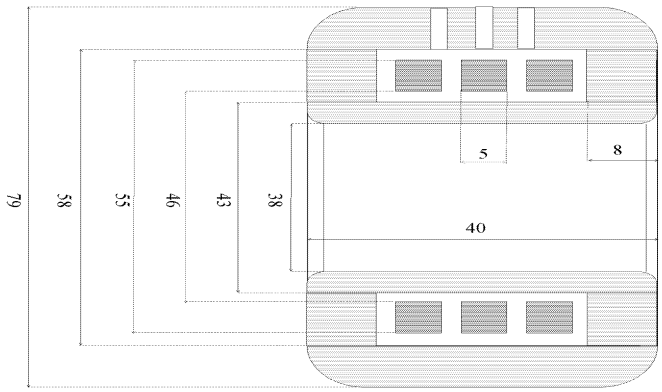

Fig. 6. Cross section of the shielding torus. Mumetal torus are in dark and winding are not represented.

C. *How to increase the secondary ampere-turns?*

To increase the secondary ampere-turn over the standard winding limitation, we can add more copper turns or use superconducting wires.

1) *Copper winding*

To measure current above 5 kA or 10 kA (the limitation of the standard copper winding), we must also use shielding around the mumetal torus. Then, new secondary winding can be wound: the main parameter is the dimension of the hole inside the measuring head and the maximum power allowed in the copper winding. With losses of 10 W and a hole of 25 mm, 30 kAt can be expected.

2) *Superconducting winding*

With superconducting wire current density can be higher and loss are not any more a limitation. We built a 10 000 turns of 0.224 mm diameter wire with critical current of 26 A at 5 T. The internal hole was 30 mm large.

Each superconducting circuit must have a protection circuit to avoid the burning of the superconducting wire when it quenches. We can use differential inductive voltage subtraction or a classical resistive bridge with a small modification to prevent current leakage during ramping. We connect three pairs of diodes (Fig.7). In addition, we replace the dump resistance by two Zener diodes mounted in opposition.

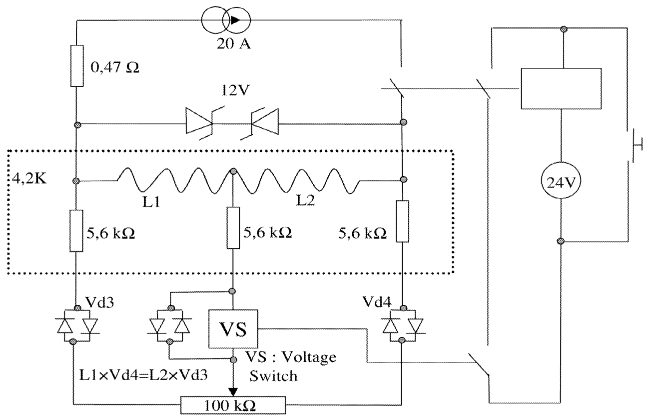

Fig.7 : Quench protection circuit used.

IV. TESTS RESULTS

Up to now, the DCCT is working up to 38kA with a precision better than 20 A controlled by the output valid signal. The improvement of conductor centering inside the measuring head should to increase this value. The excitation current and the secondary voltage are presented at 36kA (Fig.8). The shielding increases the inductance of the secondary winding (L ~ 1 H for 10 000 turns without taking account magnetic material) and decrease the precision and time reaction. The large variation of the secondary tension does not procure a large variation of the secondary current because of this self-inductance value: 1V/1H ×2ms=2mA.

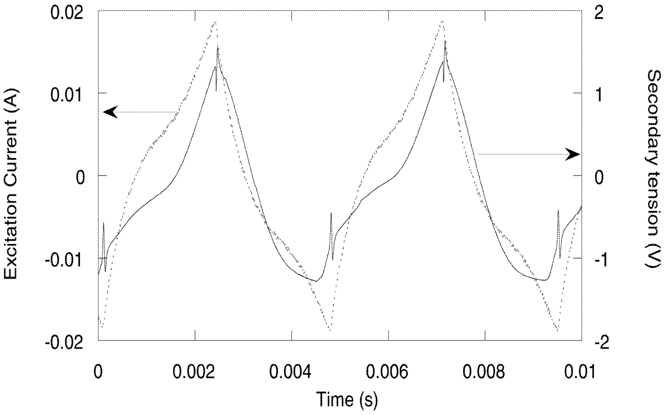

Fig. 8: Excitation and secondary voltage at 36kA.

V. CONCLUSION

We adapted a standard low cost DCCT for cryogenic temperature. We have pointed out 2 kinds of limitation that we have overstepped: the secondary ampere-turn value (current or number of turn) and the magnetic field (back around and sample measuring current). We had measured up to 38kA at 4.2K with a precision better than 10^{-4}. Higher current measurement can be performed with a better centering and current distribution of the conductor inside the measuring head.

Hitec examine the possibility to sell directly a modified electronic module of the Macc+ for measurements at low temperature.

VI. ACKNOWLEDGMENT

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VII. REFERENCES

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