ISTITUTO NAZIONALE DI FISICA NUCLEARE

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INFN/TC-86/12
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SUMMARY

Many important advances in power conversion have occurred during the past years, but many of these new techniques are just now finding their way into high power, high current power supplies.

This paper describes the main characteristics of power supplies, ranging from 10kW to 20kW, that have been designed using the "switchmode" regulation technique.

Quantitative performance comparison with an alternate conventional solution is presented. Design considerations on topology, operating mode, and thermal constraints are discussed.

1 - INTRODUCTION

The isochronism requirements for all the accelerated particles in a superconducting cyclotron is achieved with a proper trimming of the magnetic field.

In the Milan superconducting cyclotron the great part of this trimming is done by different excitation of the two sections of the main superconducting coils and then by excitation of proper trimming coils wound on the hills of the machine.

A good investigated solution, in terms of residual r.m.s. magnetic field against cost and complexity of construction, foreseen twenty coils for each hill with a uniform radial distribution. (1)

A total number of 28 power supplies is essential for their excitation.

The original solution adopted for the construction and assembling of the trim coils power supplies have induced the authors to write this paper.

2 - LOAD REQUIREMENTS

The main characteristics of the coils are listed in table I. (2)

The resistance values and rated current of the trim coils are rather different; this justify the choice of different sizes for the power supplies.

The currents of the trim coils required for the acceleration of ions with different charge to mass ratio (Z/A), are shown in Fig.1; these data indicate that the current intensity and polarity change in each trim coil if different ions will be accelerated.

TABLE I - Trim coils characteristics

T.C. #	N turns *	L (uH) *	R (40 C) (mOhm) *	Imax (A)	Vmax (V)	number of power supplies
1	14	39.5	15.50	400	13.8 (38.6)	3 (1)
2	14	46	16.80	"	14.8 (41.7)	3 (1)
3	14	55	17.75	"	44.0 (15.6)	1 (3)
4	14	61	18.90	"	46.8 (16.5)	1 (3)
5	10	36.5	10.40	"	26.4	1
6	12	54	12.95	"	32.5	1
7	10	43.5	11.73	"	29.6	1
8	10	45.5	12.51	"	31.4	1
9	10	49.5	12.84	"	32.2	1
10	12	72	15.66	"	39.0	1
11	10	56	13.90	"	34.8	1
12	10	60.5	14.50	"	36.2	1
13	10	62.5	15.18	"	37.8	1
14	12	89	18.47	"	46.3	1
15	10	70	16.55	"	41.1	1
16	10	73.5	17.10	"	42.5	1
17	10	76	17.49	"	43.4	1
18	10	81	18.25	"	45.2	1
19	12	120	22.38	500	24.2	1
20	6	36	14.92	500	16.7	1

* - values are for a single coil.
Conductor types:
T.C.#1 to #4 : copper 3/16" square hollow (hole diameter = 1/8")
T.C.#5 to #20: copper 1/4" square hollow (hole diameter = 3/16")

Note 1: Vmax = Imax [(n * Rc) + Rlead]
where: n=2 or n=6
Rc = resistance of 1 coil @ 40 C
Rlead = resistance of 50 meters of cable (240 sq.mm)

Note 2: The data in parenthesis are referred to harmonic or trim connection of the coils. (1)

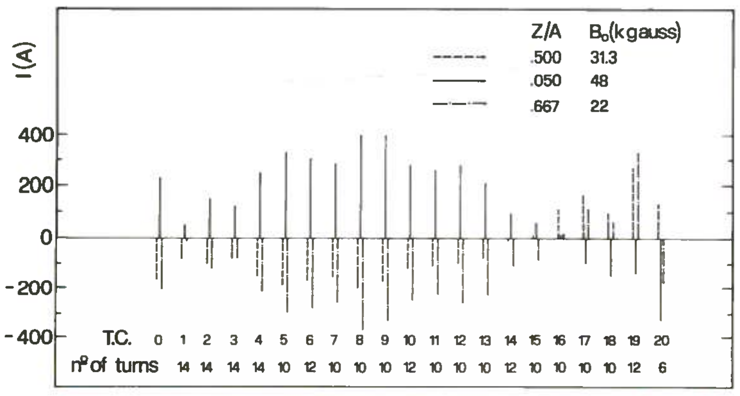

Fig.1 - Trim coils current settings for the indicated charge to mass ions ratio.

3 - POWER SUPPLIES SPECIFICATIONS

The design and the construction of the power supplies have been done in accordance with technical specifications and descriptions issued by INFN; these are largely described in a particular technical note.(4)

In this part we only resume their most important requirements which are listed in Table II.

Power supplies output ratings and number of size types was not prefigured since it was foreseeable that for each manufacturer, and/or for each proposed technology, a different optimum, in terms of cost, design complexity and utilisation factor may be reached.

Moreover, although not explicitly indicated in the technical specifications, it would be better, for reasons of standardisation, simplicity and maintenance, that all the power supplies, in the various sizes, are based on the same design and, if possible, use the same type of components.

Because of the cabling costs and losses involved it has been decided to locate the power supplies at the closest distance from the cyclotron machine. This will therefore require compact and relatively small power supplies of the highest possible conversion efficiency, since both floor space and cooling needs are at a premium in the cyclotron building.

4 - POWER SUPPLIES SYSTEM OUTLINE

The first approach to the overall design was related to the packaging requirements. The limited floor space and volume allowed forced the designers to accurately investigate all the factors that necessarily should be assessed early in the design stage, including heat transfer, maintainability, major components allocation, transport and installation.

Taking into account the necessity to reserve space for common parts and circuits, (computer control interface, cooling water collectors and a.c. power line distribution), the available floor space for each power supply module resulted of about 0.25 sq.mt. The choice, in fractioning the 10 sq.mt floor space, was:

- 5 cubicles of 2mt (width) x 1mt (depth) x 2.2mt (height).
- 7 sectors per cubicle: 6 sectors assigned to power supplies modules, 1 sector for common devices (see Fig.9). The two sectors in excess reserved for spare or utility power supplies.

Table II

Mains input: 380V, +10%/-10%, 3-ph, 50Hz

Max d.c. output current: 400A or 500A (*)

Max d.c. output voltage: 24V or 36V or 48V (*)

Operating modes: "current mode" and "voltage limit mode" (with automatic crossover)

Current stability (8 hour): +/- 125mA (on all range)

Current reproducibility: +/- 125mA (on all range)

-after warmup and against:
- +/- 5% line voltage variations
- +/- 2 C water temp. variations
- +/- 5 C ambient temp. variations
- +/- 10% load resistance variations

Output ripple and noise (PARD = Periodic & Random Deviation) :
(in current mode / resistive load)

-RMS value (20 Hz to 300 Hz): < 50mV RMS
- pk to pk (300Hz to 150kHz): < 100mVp-p

Efficiency: > 70% (full output power) / > 60% (1/2 output power)

Line power factor: > 0.9 for output power 25% to 100%

Cooling system: demineralized water or natural air (no fans)

Total surface covered (28 power supplies): < 10 sq.meters

Radiated and conducted EMI : according to VDE 0875 grade N

Output polarity reversal : automatic, by power contactors and flywheel diode bridge protection.

Protections and safety features :
- -heatsink and cooling water overtemperature protection
- -a.c. line phase failure protection
- -load overresistance protection
- -coils overtemperature protection
- -doors interlock cutoff

Controls:
- -Local: a.c. and d.c. power on/off switches, current and voltage adj., alarm and status indicators, analog panel meters and digital temperature readout.
- -Remote: complete remote operation via computer serial interface; current programming, voltage and current monitoring, polarity reversal and status readback.

(*) - Voltage and current ratings combinations to be selected to fulfil the various trim coils requirements.

4.1 - Conversion technique selection

Subsequent design step was to define a set of alternate conversion circuit configurations, compatible with the physical and electrical specifications, and operate a comparison.

Only two major types of conversion techniques appeared suitable for the purpose:

- Controlled rectifiers pre-regulator + linear post-regulator
- Uncontrolled rectif.+ 20kHz switchmode regulator (buck-type)

The most important parameters to be considered in the choice of converter type are compared in Table III. The comparison is relative to the two foreseen sizes having higher ratings.

TABLE III

	SCR + LINEAR REG.		SWITCH-MODE REGULATOR	
Output ratings:				
-current:	500A	400A	500A	400A
-voltage:	36V	48V	36V	48V
-power:	18kW	19.2kW	18kW	19.2kW
Losses (estimated):				
-linear regulator:	2500W	2000W	--	--
-switchmode regulator:	--	--	2000W	1600W
-transformer:	900W	950W	700W	750W
-auxiliary circuits:	200W	200W	200W	200W
Total losses:	5600W	4750W	3600W	3300W
Efficiency:	76%	80%	83.3%	85.3%
Power factor (full load):	0.8 to 0.85		> 0.98	
" " (25% load):	< 0.6		> 0.93	
Line current harmonics:	high		low	
Line brownout immunity:	poor		good	
Output ripple:	very low		low	
Relative cost:	1		1.1	

The "switchmode" design seems to offer other minor advantages in terms of weight and volume (about 5% less), acoustical noise, and conducted/radiated electromagnetic interference (EMI).

The choice of the switchmode technique appeared largely justified. Besides, as can be easily calculated, the higher cost of this solution may be entirely compensated by the saving in energy expenses, in a medium-term period of 5000 to 10000 hours, depending on utilization conditions.

4.2 - Converter topology and other design choices

Components limitations in voltage and power ratings impose to employ a number of paralleled dc/dc power conversion stages, operating from a low voltage source derived from the supply mains through a three-phase transformer and bridge rectifier.

Step-down buck regulator configuration (see Fig.2) is the natural choice for the power stages. Regulator control is accomplished by means of independent pulse-width modulator (PWM) circuits, operating at constant frequency and synchronously.

Other converter topologies (half-bridge and full-bridge PWM), operating from a relatively high voltage source (200V to 300V), obtained by means of an autotransformer and a bridge rectifier, have been examined, but safety consideration and the foreseeable problems deriving from the cooling of the mains side connected power switching devices, suggested to discard them. (3)

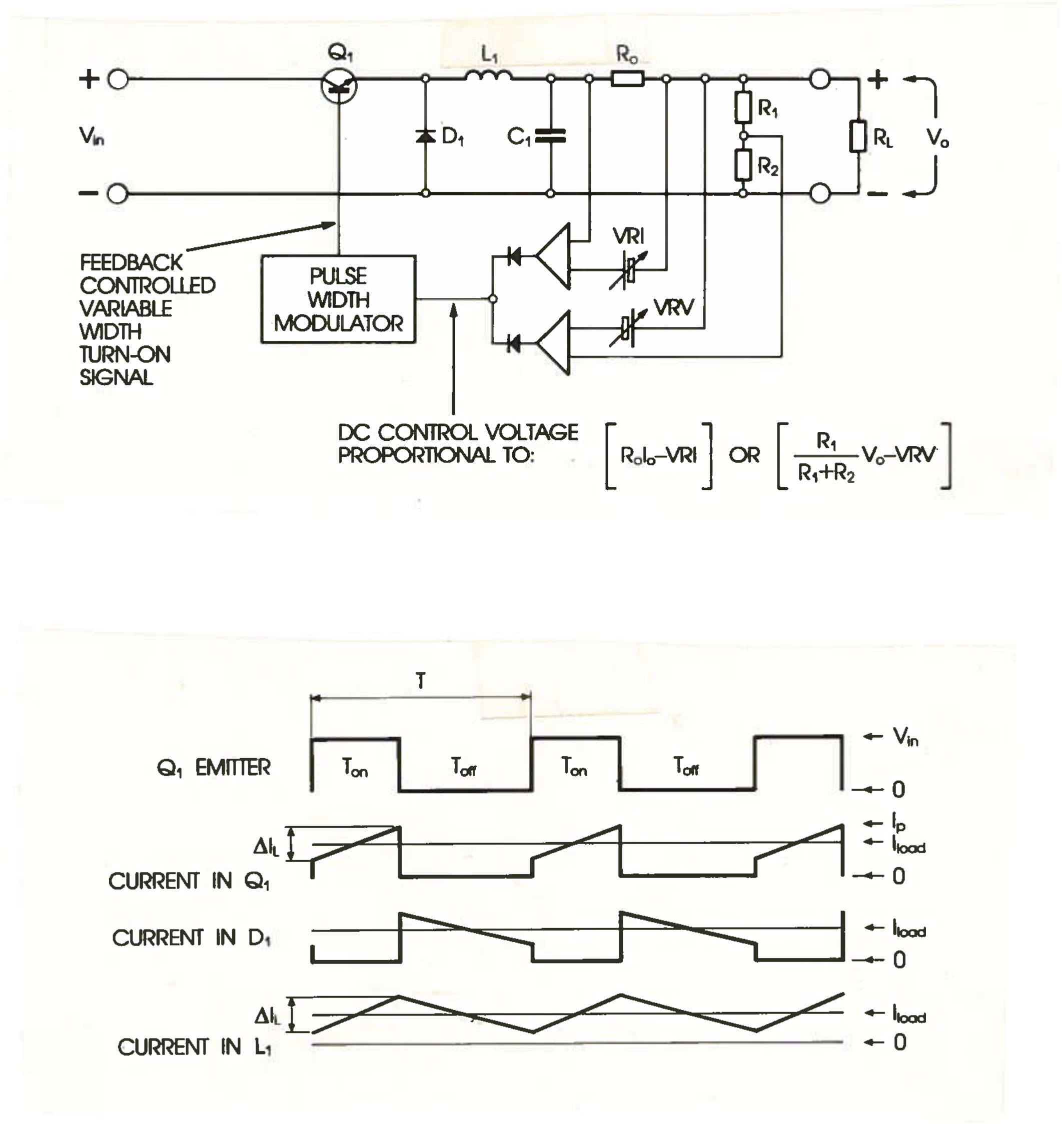

Fig. 2 - Basic buck-type regulator

Minimization of both switching losses in power transistors and core losses in storage inductors required to adopt a value of operating frequency (18.5 kHz) just a little beyond the audibility limit. Higher optimum conversion frequency could be reached employing MOS-FET power switches instead of bipolar transistors, but their high price and limited availability, at the time of design process, were discouraging.

The choice of input source voltage value is also related, apart from power devices voltage ratings, to an optimum balance of rectifier bridge losses and switching losses. Maximum duty-cycle and line drop-out margins are other determinant factors. This nominal input voltages were selected:

- for 48V output max voltage power modules: Vin = 75V
- for 24V output max voltage power modules: Vin = 43V

Equal current sharing among the power stages operating in parallel is mandatory. For this purpose a dual-loop control has been adopted (see par.4.4).

Taking into account single device capabilities of power transistors, flywheel diodes, inductors and capacitors, a minimum number of 16 paralleled stages (channels) for the highest output current rating of 500A has been determined. A scaled down version of the power module, underequipped to only 14 channels, appeared well suited to the 400A output current rating.

4.3 - Power modules sizes and ratings definition

For the purpose of determining and minimize the various sizes of power modules that can adequately match the trim coils requirements listed in Table II, the following considerations are helpful:

- At a given maximum output voltage rating, cost varies almost linearly with output current rating.

- At a given maximum output current rating, cost varies only slightly with output voltage (or power) rating. A rough estimate gives a 5% cost reduction for one-half output voltage.

The above applies to the anticipated configuration where many identical regulator stages operate in parallel and for relatively low output voltage converters for which low-end rated voltage dependent components are used.

Three types of power modules have been selected. The Table IV indicates their output ratings and the relative trim coils assignment.

TABLE IV

Type	Q.ty	Vmax	Imax	Trim Coils #
A	6	24V	400A	1-2
B	8	36V	500A (*)	17-18-19-20
C	14	48V	400A	3 to 16

(*) - Operation at higher voltage is allowed at reduced current. Linear derating to 400A @ 48V, applied through automatic power limit circuit.

4.4 - Dual loop current control

The necessity of equal current sharing among the power stages (channels) operating in parallel suggested to employ a separate PWM regulator for each of the channels, and to operate them in a slaved configuration.

The following part of this paragraph provides a brief description of the principle of operation of the overall control circuit and of the automatic equal current sharing feature (see Fig.3).

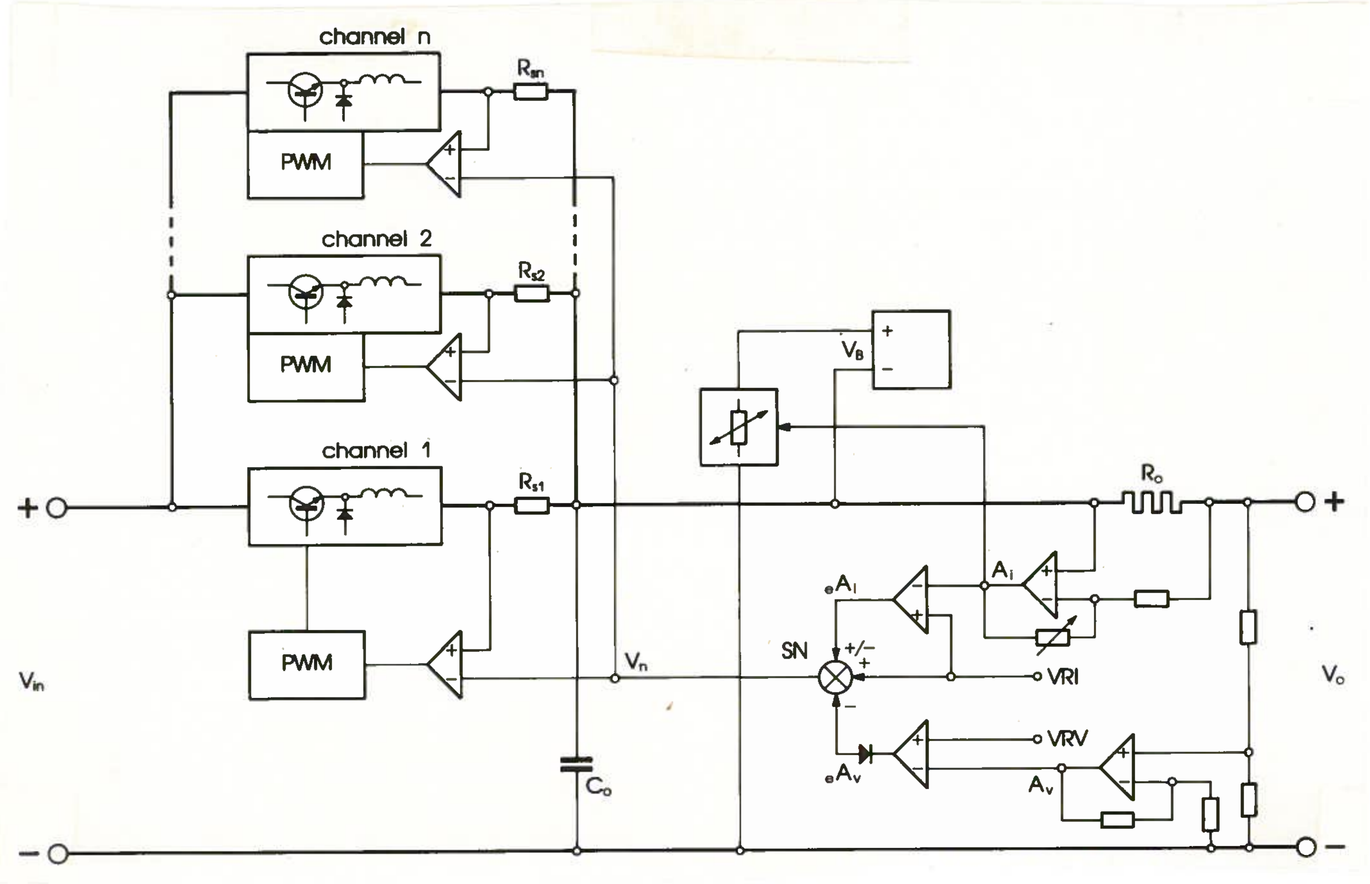

Fig.3 - Control circuit block diagram

At channel level (inner loop) the voltage developed across each channel current sensing resistor (Rs1; Rs2; ...Rsn) is directly compared, by the PWM regulator input amplifier, to the voltage Vn resulting at the summing node SN. Summing node voltage Vn is primarily dependent upon the "current mode" variable reference voltage VRI (i.e. current programming voltage). The node level is also dependent on the correcting signal eAi, resulting from the comparison of the same reference voltage VRI to the voltage Ai, proportional to the total output current. This performs the "outer loop" section of the current control circuit.

In order to easily perform final testing and to ensure operation, at reduced maximum current, in the event of failure of one or more channels, the gain of the current sensing amplifier can be presetted, to one of the discrete values

$$Gi(n) = 16/n \ast Ai/Ro \ast Io$$

where n is the number of channels effectively operating in parallel.

In the ideal condition the amplitude of the correcting signal eAi is zero. Various non-idealities, most of all related to the PWM control circuit (ramp slope and thresholds) and to the switching power transistors (transition and storage time), will determine deviations of eAi of either sign.

In the "voltage limit" mode of operation, the Av voltage, proportional to the output voltage, is compared to the VRV reference voltage (i.e. voltage limit programming voltage). The resulting error voltage eAv can override the influence of VRI and eAi at the summing node, and acting as a common reference voltage for all the paralleled channels, provides equal current sharing even in the constant voltage mode of operation.

For the purpose of mantaining a significant "on" pulse duration to the power switching transistors, for very low values of programmed output current, an active bleeder circuit, operating from a bias source Vb, ensures that the current supplied by the regulators does not drop below a minimum useful value.

5 - POWER MODULES GENERAL DESCRIPTION

Fig. 4 shows the block diagram of the power supplies modules. The depicted functional division corresponds very nearly to the assignment of the physically separate units described in the following paragraphs.

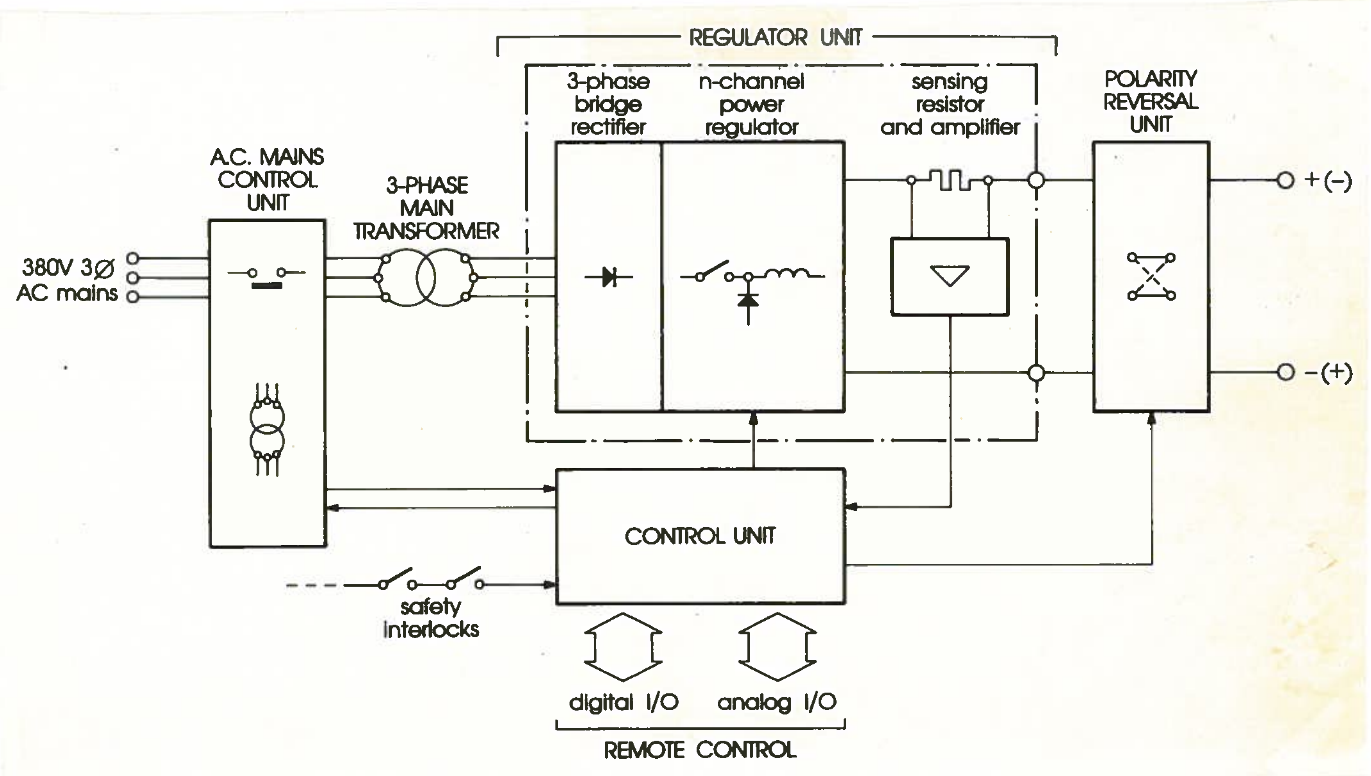

Fig.4 - Power supply module block diagram

5.1 - A.c. mains control unit.

Comprises the 3-phase main power contactor and thermal relay, the 3-phase auxiliary transformer, the soft-start contactor and associated current inrush limiting resistors, and other control devices.

The unit is allocated on the lower front end of the assignated cubicle section. Tilting mounting allows easy inspection of internal components.

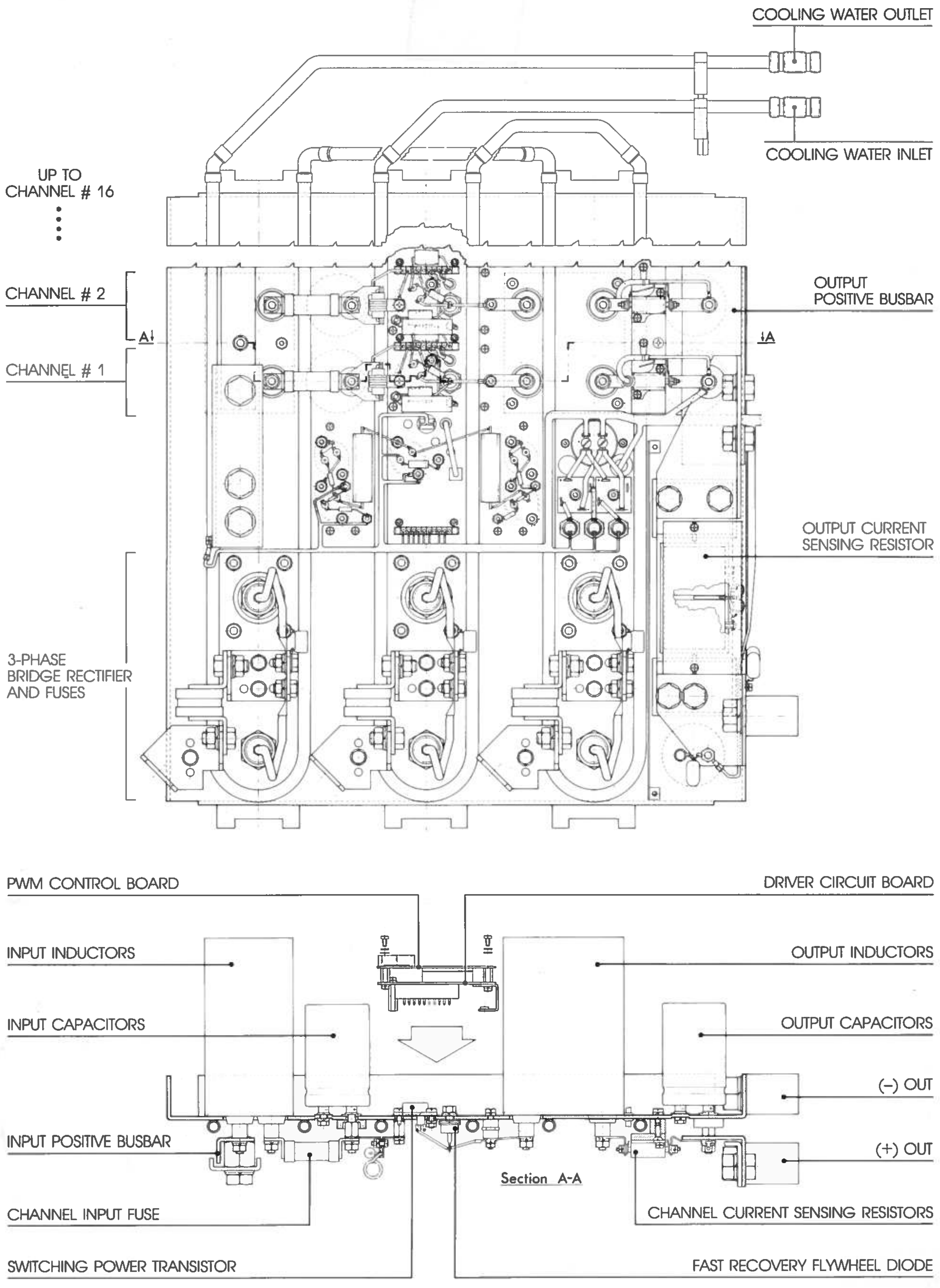

Fig.5 - Regulator unit baseplate assembly (components layout).

5.2 - Main transformer.

Two sizes have been foreseen: 12 kVA for type "A" modules and 24 kVA for "B" and "C" modules. The transformer is convection cooled and is placed at the base of the cubicle section, behind the a.c. mains control unit.

5.3 - Regulator unit.

This unit includes all the major heat dissipating semiconductor devices and components:

- 3-phase diode bridge rectifier
- input inductors and capacitors
- switching power transistors
- fast recovery diodes
- snubber networks
- output inductors and capacitors
- channel current sensing resistors
- output current sensing resistor
- active current bleeder transistors
- bias supplies rectifiers
- PWM control and driver boards
- bias supplies regulators and control amplifiers board
- current and voltage sensing amplifiers board

All the above devices are mounted on a large water cooled, 3mm thick, copper plate. The component layout and interconnection are illustrated in Fig.5. The copper baseplate coincides with the negative output side of the regulator. In Fig.5 only the first two of the sixteen PWM regulators (channels) are shown. In the scaled-down versions (Iout=400A) the components of the upper last two channels are not mounted.

Input and output inductors are assembled two by two (separate windings on a single "C" type grain-oriented core), and enclosed in metal cases potted with quartz powder filled epoxy resin, for better heat transfer.

Also the PWM control and driver circuits are grouped for each pair of channels. The corresponding printed circuits boards, superposed and interconnected, are mounted behind the area occupied by the switching transistors and flywheel diodes. A daisy-chain flat cable connects all the PWM control boards to a common "control amplifiers" board.

The output current sensing resistor is built using selected manganin plate of low temperature coefficient. The resistor element, insulated by means of thin sheets of mylar, is interleaved between two brass blocks, and fixed, through bolts, to the water cooled baseplate.

To minimize noise pick-up, the board that comprises the current sensing amplifier is directly mounted over the sensing resistor. On the same board is located the voltage sensing amplifier. Voltage error sensing is performed in proximity of the two large sized output terminals.

The baseplate assembly is vertically mounted, through insulating spacers, in a drawer frame that is supported on a pair of heavy duty telescopic slides located at the top. A third horizontal bottom slide, with lock-out arrangement, enables the unit to be fully extended and locked for easy inspection and servicing (see Fig.6 and Fig.10).

Input connections to the main transformer secondary, and output connections to the polarity reversal unit, are made by means of flexible, single conductor, power cables. Flexible, helically wound, nylon tubing is used to connect the cooling water inlet/outlet to the cubicle water collectors.

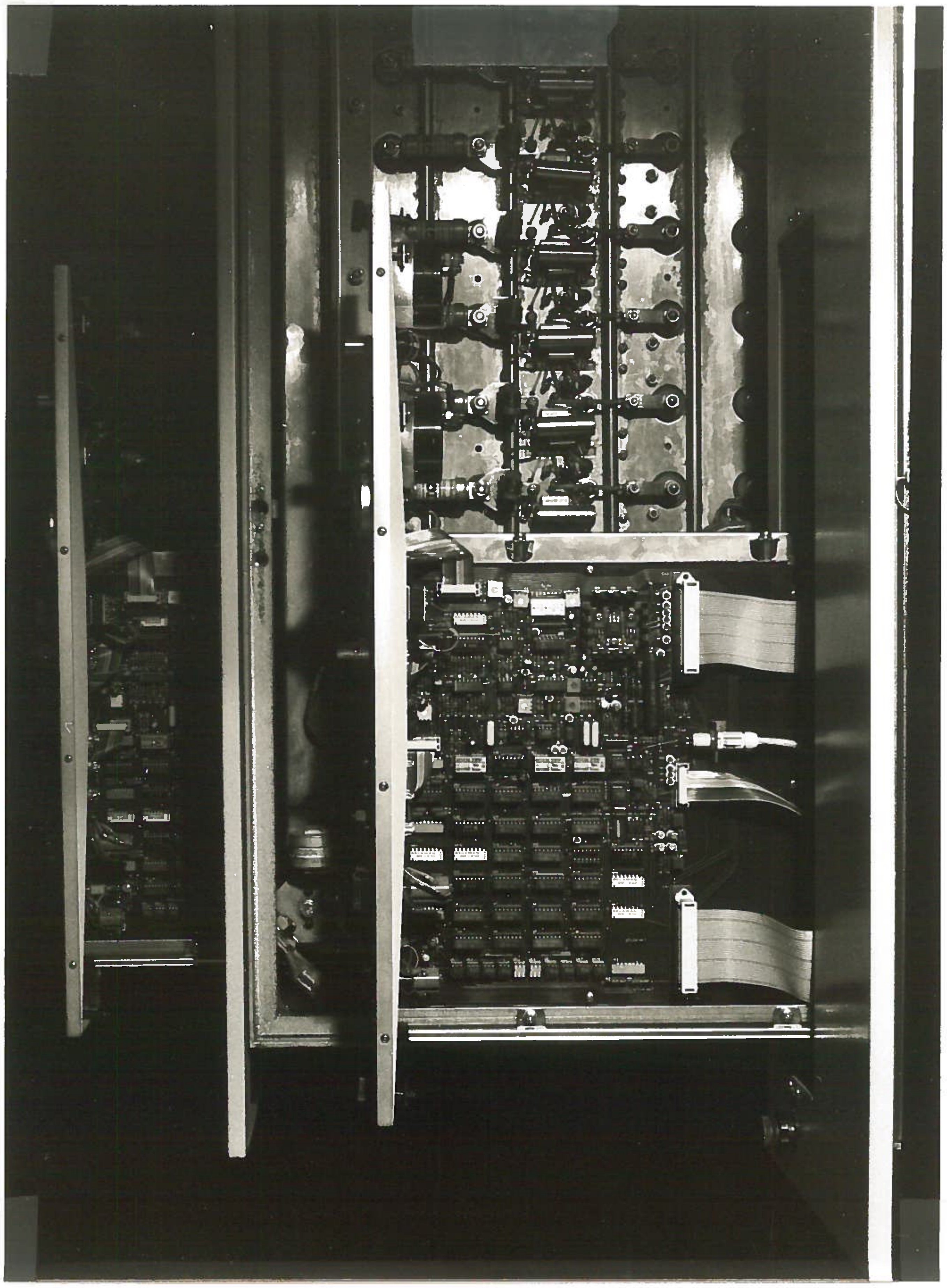

Fig.6 - Control unit and regulator channels.

5.4 - Control unit

This unit features all the control and supervisory functions related to the operation, in "local" mode or in "remote" mode, of the power supply module. The most important functions provided are:

- Local analog programming of the supply output current and voltage, by means of multiturn potentiometers.
- Remote analog programming of the output current.
- Local indication (moving coil meters) and remote monitoring of output current, effective output voltage and programmed limit voltage.
- Local or remote power on/off sequencing (ac on/off ; dc on/off) and other control function (polarity reversal; limit voltage readback; alarm reset). All remote control lines are optically isolated.
- Local status and warning indicators (LED) and optically isolated remote status monitoring.
- Digital temperature meter and alarm indicators for heatsink and cooling water.
- Load over-resistance shutdown circuit.

The layout of front panel controls and indicators is shown in Fig.7. The control unit assembly composed of the front panel and of a large printed circuit board, is mounted, as a drawer, on the front of the regulator unit frame. Two telescopic slides allow complete extension of the control unit. Electrical connection is made through a pair of flat cable connectors.

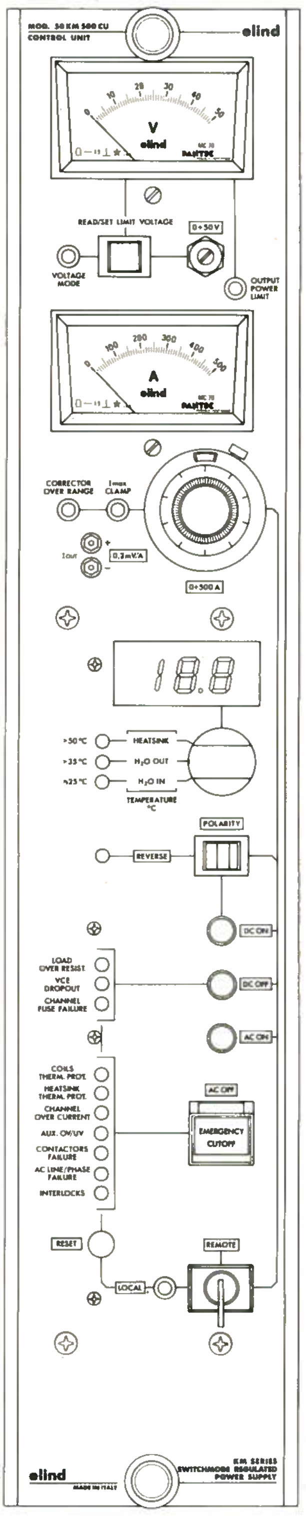

Fig.7 - Control unit front panel

5.5 - Polarity reversal unit

This unit employs four heavy-duty, aerospace type, power relays (Cutler-Hammer, 6041 series), associated, in a bridge configuration, to four high current flywheel diodes.

The power relays and diodes are mounted on a frame of thick, nickel plated copper crossbars, acting as heatsink for relays contacts and as terminations for input/output power cables.

Flywheel diodes are required to mantain a current path in case of power supply shutdown, and also, in the event of a quench of the superconducting coils (2), to convey the induced energy to the output capacitors bank of the power supply module.

The polarity reversal unit is located at the rear side of the cubicle section, behind the regulator unit.

.6 - Cooling system

As reported in par. 4.1, a worst case value of 3600W of total losses, for the type "B" power module (500A/36V), was anticipated.

The limited volume (0.5 cu.mt) assigned to each module, apart from other considerations (room heat transfer capability, cooling water availability), made the liquid cooling choice the only possible.

As seen at par. 5.3, the great part of the heat dissipating components are concentrated on the water cooled baseplate of the regulator unit. In a good approximation, it has been estimated that more than 80% of the about 2800W dissipated in the regulator unit are transferred to the cooling water. Since the total losses are 3600W, an amount of 1300-1400W must be dissipated in air. This give a heat concentration, in the cubicle, of less than 3W/cu.dm (0.05W/cu.in), a figure for which natural convection cooling is fairly adequate. Moreover, one can rely on the aerated, and slightly pressurized, floating floor of the room where the cubicles will be allocated.

The water distribution is accomplished by means of two manifolds located at the top of the cubicle. Water is filtered at the inlet point. Manual ball valves allow easy disconnect of each power module, and solenoid valves provide selective water cut-off when the modules are not powered. High performance stainless steel tube fittings and valves are used throughout. Flexible nylon tubing, helically wound, allow extraction of the regulator unit for inspection and maintenance.

In the type "B" power modules (Imax=500A), also the contact terminations of the polarity reversal power relays are water cooled.

Some details of the cooling system are shown in Figure 8.

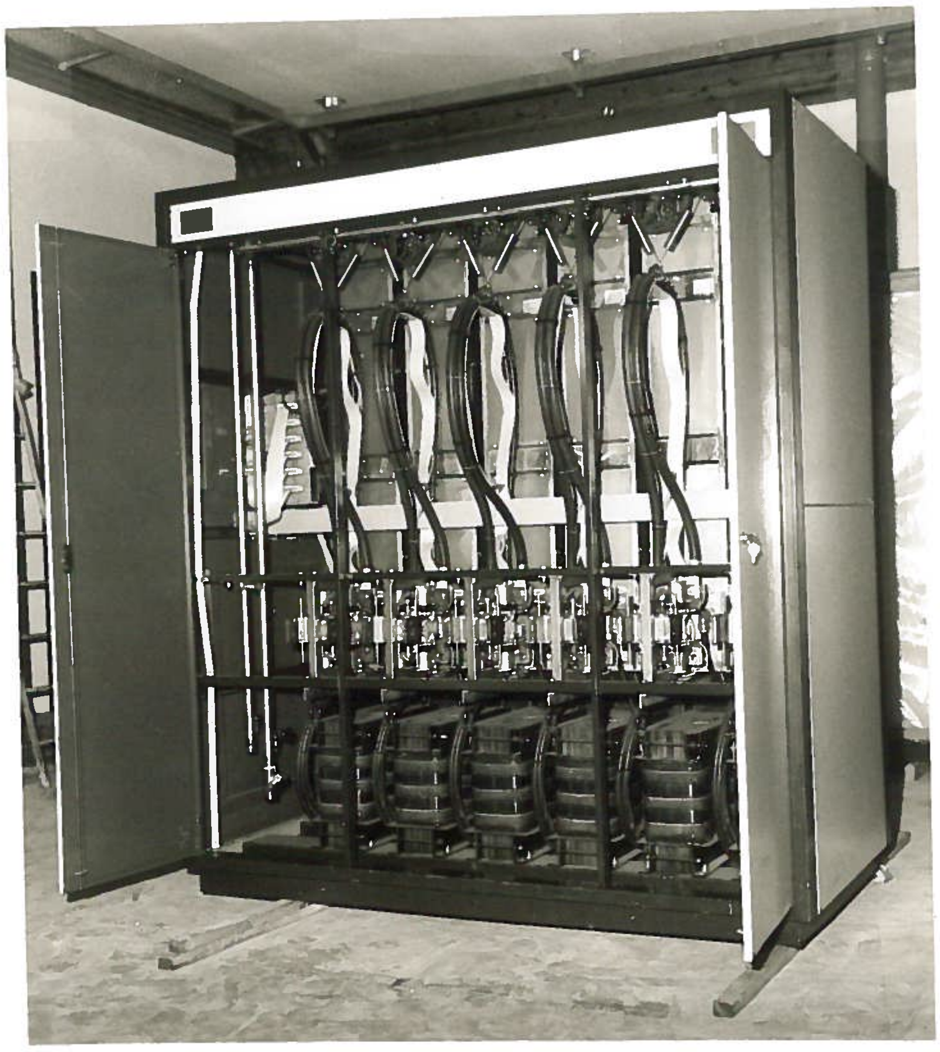

Fig. 8 - Power supplies cubicle, rear view.

Fig. 9 - Power supplies cubicle, front view.

5.7 - Remote control interface

Both analog and digital control of the cluster of up to six power modules assembled in each cubicle is provided by a self-contained, microprocessor based, modular control subsystem (Analog Devices / muMAC-4000).

The control subsystem, composed of a master board and three expander boards mounted in a card cage, is placed in the rightmost section of the cubicle.

Analog outputs, dedicated to output current programming, feature 12-bit resolution, +/-1000V isolation, bumpless transfer and programmable slew rates. Analog inputs, assigned to output current and voltage readback, offers input protection, +/-1000V isolation, high common mode rejection and 13-bit A/D conversion.

Digital I/O channels, for remote control functions and status monitoring, are optically isolated (+/-300V)

The subsystem can operate with any host computer which has a 20mA or RS-232C serial port. Serial link allows use of either the party line (all clusters series connected) or radial (one port per cluster) system configuration.

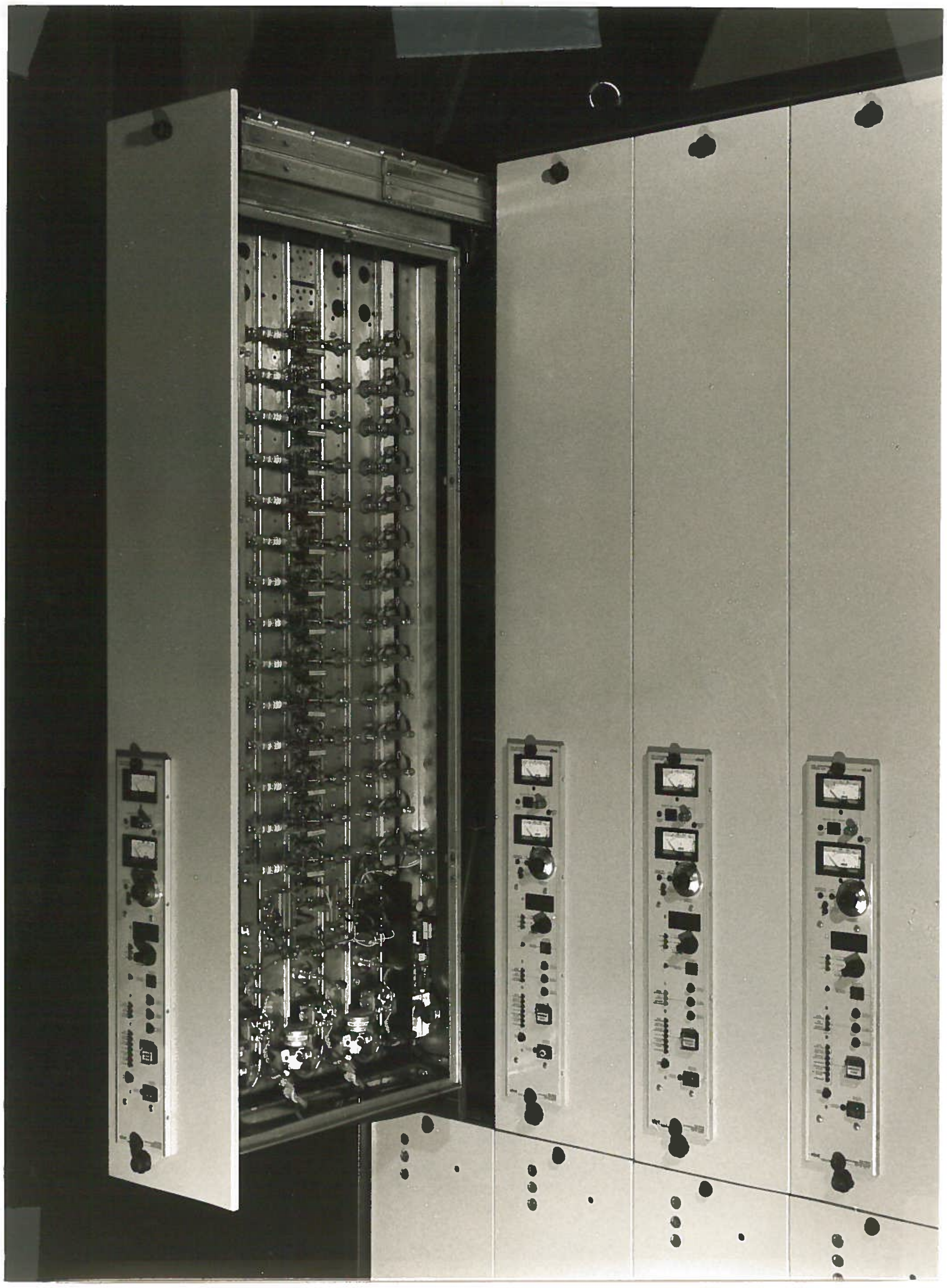

Fig.10 - Regulator unit, fully extended.

6 - CONCLUSIONS

The feasibility and convenience of processing up to 20kW of power with switchmode technique, at high current levels, has been demonstrated by successful design, development, construction and testing of the entire set of 28 power supplies required for the trim coils of the superconducting cyclotron.

Testing was conducted, under a variety of conditions, for stability, output ripple and noise, line and load regulation, input power factor and efficiency. The test results were well within the specification limits and accurately matched the objectives and the estimates upon which the "switchmode" design decision was based. In particular, efficiency values higher than 84% for the 500A/36V units, and over 86% for the 400A/48V units, were measured.

7 - ACKNOWLEDGEMENTS

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