POWER CONVERTERS OF THE MAIN DIPOLE AND QUADRUPOLE MAGNET STRINGS OF THE ANTIPROTON DECELERATOR AT CERN

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Abstract

The two main power converters for the dipoles (D) and quadrupoles (Q) are presented as part of the complex power converter system of the Antiproton Decelerator. The operational requirements and the performance specifications for deceleration from 3.5 to 0.1 GeV/c are discussed. The layout and design of the power part, consisting of a 12-pulse thyristor rectifier and a switch-mode parallel active filter (AF), and of the precision regulation are described. The alternatives for integrating the AF into the current and voltage regulation loops are outlined. Problems encountered and results of tests are reported.

1 INTRODUCTION

The Antiproton Collector (AC) at CERN has been converted into an Antiproton Decelerator (AD) ring [1] for which the two main power converters of the AC had to be considerably modified [2].

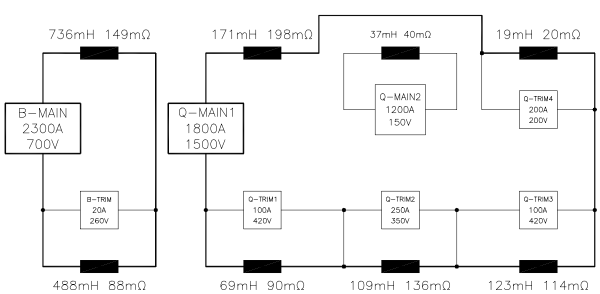

Figure 1: The power converter system for the AD.

2 AD MAIN MAGNET SYSTEM

The main magnet system of the AD consists of 24 dipoles, connected in series and excited by the power converter B-Main, and 57 quadrupoles. Of these, 53 are fed in series by the converter Q-Main1, while 4 additional quads are powered separately in series.

Trim power supplies, and orbit corrector power supplies, are connected across groups of B and Q magnets.

This system is schematically shown in Figure 1.

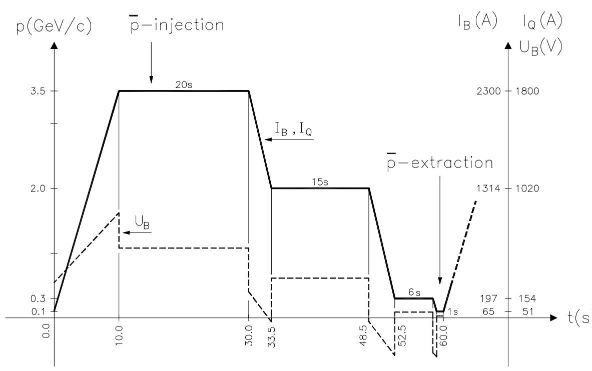

Figure 2: The AD power converter operating cycle.

3 OPERATIONAL REQUIREMENTS

During an AD cycle of ~60 s the current in the B and Q magnets, being roughly proportional to particle momentum, is ramped up in ~10 s. Antiprotons, created by a 26 GeV/c proton beam on target, are injected at 3.57 GeV/c, cooled and decelerated down to 100 MeV/c.

The main power converters are required to perform:

- Dynamic current range as large as 35 to 1.
- High current precision and reproducibility.
- Low residual output voltage ripple.
- Very low tracking errors relative to current reference.
- Short (<100 ms) slope change transition times.

The AD converter operating cycle {particle momentum (p), current of B-Main (I_B) and Q-Main1 (I_Q) and voltage of B-main (U_B) converters} is shown in Figure 2.

Table 1 shows the performance and load specifications.

Table 1: Performance requirements and load specifications.

Power converter	Nominal DC ratings [A - V]	Tracking error $\Delta I/I_n$ (♣) at 3.57 and 0.1 GeV/c	Current I_n at 3.57 and 0.1 GeV/c [A]	Magnet load impedance and time constant L - R - τ [H - Ω - s]
B-Main	2300 - 700	1.10^{-4} and 1.10^{-3}	2300±0.23 and 65±0.065	1.224 - 0.239 - 5.17
Q-Main1	1800 - 1500	1.10^{-4} and 1.10^{-3}	1800±0.18 and 51±0.051	0.49 - 0.558 - 0.88

(♣) $\Delta I/I_n$ is referred to nominal current at 3.57 and 0.1 GeV/c respectively.

(*) At CERN during French National Service.

4 AD MAIN POWER CONVERTERS

4.1 Power part

4.1.1 Thyristor rectifiers

The power circuit of the 12-pulse SCR (Silicon Controlled Rectifier) rectifiers is shown in Figure 3.

The modifications to the former AC power converters include:

- Replacing free-wheeling (FW) diodes by SCRs.
- Replacing the SCR gating circuits.
- Reducing the filter capacitance and inductance.
- Adding a de-coupling choke and an active filter.
- Feedback of the rectifier current by a LEM sensor.
- Implementation of new regulation and interlock electronics and computer control interface.
- Modification of bus-bars and water circuits.

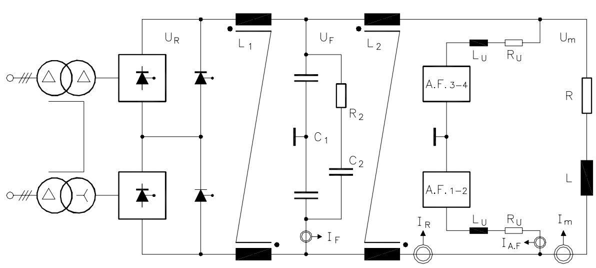

Figure 3: The power circuit of the SCR rectifiers.

Eliminating the passive filter of the SCR rectifier, and having the 600 Hz current ripple attenuated by the active filter (AF) alone, has shown to be not possible.

After modification, the main AD power converters consist of two 6-pulse SCR bridges in series, fed by double 18 kV DD-DY {D=delta; Y=star} transformers, with FW SCRs and a lighter ($f_o \cong 200$ Hz) DC passive filter including a new choke L_1 (0.75 mH). The filter leaves a residual 600 Hz load current ripple of ~40 mA_{pp}. The previous filter choke (2 mH) is used to de-couple the SCR rectifier from the active filter.

The characteristics of the SCR rectifiers of the B-Main and Q-Main1 converters are collected in Table 2.

4.1.2 Active filter

A parallel active filter, composed of IGBT (Insulated Gate Bipolar Transistor) full-bridges in series, driven by the same 16 kHz PWM (Pulse Width Modulation) patterns and dimensioned for the full output voltage, reduces current errors, in particular during ramps and transients below 300 MeV/c momentum.

The active filter of the B-Main converter is rated ±900 V-30 A and consists of a D-YY insulating transformer and two diode rectifiers, DC link LC filters and water cooled IGBT-bridges; each bridge is equipped with its own LC-RC passive filter.

The active filter of the Q-Main1 converter is rated ±1900 V-30 A and is made up of twice the B-Main AF assembly in series.

An inductance (~1 mH) and a resistance (~1 Ω) are connected in series to the output of the AF.

The power circuit of the AF is shown in Figure 4 and the AF characteristics are collected in Table 3.

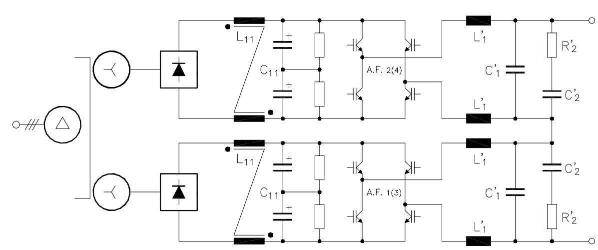

Figure 4: The power circuit of the parallel active filter.

Table 2: Characteristics of SCR rectifiers for Bending and Quadrupole magnets.

Power converter	Maximum-DC ratings [A - V]	Number of 6-pulse SCR bridges in series	Passive DC filter L_1 - C_1 - R_2 - C_2 [mH - mF - Ω - mF]	De-coupling inductance L_2 [mH]
B-Main	2650 - 880	2	0.75 - 0.125 - 2.5 - 0.5	2
Q-Main1	2150 - 1760	2	0.75 - 0.125 - 2.5 - 0.5	2

Table 3: Characteristics of active filters for B-Main and Q-Main1 power converters.

Power converter	Ratings [V - A_{eff} - kW]	Pulse current [A_{peak}- ms]	Number of IGBT bridges in series -- IGBT type (EUPEC)	DC-link voltage [V]	Individual filter L'_1 - C'_1 - C'_2 - R'_2 [μH - μF - μF - Ω]	Output impedance $2L_u$ - $2R_u$ [mH - Ω]
B-Main	900 - 30 - 27	120 - 100	2 -- FF400-12KF4	510 ± 10%	200 - 5 - 20 - 5	1.0 - 1.3
Q-Main1	1900 - 30 - 57	120 - 100	4 -- FF400-12KF4	510 ± 10%	200 - 5 -20 - 5	1.0 - 1.0

4.2 Regulation

The SCR rectifier and the parallel AF represent two separate sources feeding the same load, and controlled by separate but coupled current feedback loops.

A block diagram of the system is shown in Figure 5.

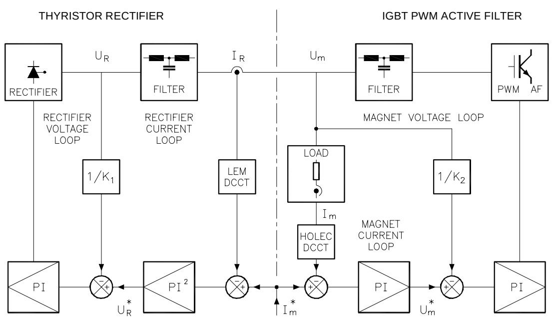

Figure 5: Regulations of SCR rectifier and AF.

4.2.1 SCR rectifier regulation

An internal feedback loop controls the voltage of the 12-pulse rectifier and a second loop controls its current after the passive filter. Two integrators in the current loop provide for minimum tracking error and, to normalize the regulations for B-Main and Q-Main1, the magnet load pole is compensated. A phase margin of 65° is obtained for a bandwidth of >10 Hz with a suitable corrector.

Without AF, the current error during transients would be an order of magnitude larger than specified.

4.2.2 Parallel active filter regulation

The purpose of a parallel AF [3] is to have most of the current delivered by the rectifier while the AF, designed for high gain and fast response, cancels the current errors during the cycle.

Thus a PI (Proportional-Integral) current loop reacts to the magnet current reference and to the feedback from a precision 10 V/I_n HOLEC sensor.

4.2.3 Matching of SCR rectifier and AF regulations.

The regulations of the rectifier and the AF are set up separately and then put together. Different schemes of matching them have been examined:

- AEG-GSI: this scheme [4] is based on a master/slave operation of the AF and of the rectifier, which is driven by an offset current reference (~1% I_n) and by the AF current feedback. When the AF current exceeds the offset level the rectifier is forced to deliver more current while the AF average current is kept constant.
- OCEM-CERN: the AF and the rectifier receive the same current reference. The average current of the AF is negligible due to the double integration in the SCR rectifier current regulation. The AF has been adjusted with the rectifier connected, but disabling the SCR gate pulses. To obtain effective tandem operation the gain and the bandwidth of the AF must be tuned. Simulations show that the bandwidth could reach 1.5 kHz, by adding an internal load voltage control loop.

5 TESTS AND COMMISSIONING

During tests, an AD current reference with nominal slopes was implemented using a function generator.

Once the rectifier and AF regulations had been set up separately, the problems encountered were mainly:

- For stable operation, the gain found by simulation of the rectifier current loop had to be reduced. Thus a larger amount of correction by the AF was required.
- The current regulation of the AF had to be readjusted for the two systems to work well together.
- The reduction of the 600 Hz load current ripple by the AF became marginal and the cutting frequency of the passive filter of the rectifier had to be lowered.
- The trim power supplies interact with the main power converter circuit increasing the current ripple and driving the AF to its stability limit.

6 CONCLUSIONS

The B-Main and Q-Main1 power converters have been commissioned using the OCEM/CERN matching scheme. The initial requirements for the running-in of AD have been met. Problems concerning stability, ripple and operation with trim supplies call for further attention as the development of the AD machine continues. The analogue rectifier regulation has in the meantime been replaced by a digital version. More simulations will allow an analysis of the system including the trim power supplies.

ACKNOWLEDGEMENTS

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