# CNAO STORAGE RING DIPOLE MAGNET POWER CONVERTER 3000A / ±1600V

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*Abstract*

This paper will describe the design and simulations of the CNAO Dipole Power Converter rated 3000A / ±1600V. The Power Converter will feed the 16+1 synchrotron bending dipole magnets of the CNAO Storage Ring. The actual design confirms how the choice of a twenty-four pulses, 4 bridges series-parallel connected, active filter, bipolar voltage, meets the stringent requested technical specification ($10^{-5}$ of maximum current for the output current residual ripple and setting resolution). The extensive modelling will also be presented. The design includes the strength of the topology design, component derating and component standardization. As the other CNAO power converters, the Storage Ring Dipole Power Converter uses the same digital controller, under licence from the Diamond Light Source.

## INTRODUCTION

A synchrotron machine, capable to accelerate either light ions or protons, will be the basic instrument of the CNAO (Centro Nazionale di Adroterapia Oncologica), the medical center dedicated to the cancer therapy, that is under construction in Pavia (Italy). The machine complex consists of one proton-carbon-ion linac that will accelerate the particles till the energy of 7 MeV/u. An injection line will transport them to the synchrotron ring where the injected particles will be accelerated and extracted with an energy ranging from 60 to 250 MeV for protons and from 120 to 400 MeV/u for carbon ions.

Protons and light ions are advantageous in conformal hadrontherapy because of three physical properties. Firstly, they penetrate the patient practically without diffusion. Secondly, they abruptly deposit their maximum energy density at the end of their range, where they can produce severe damage to the target tissue while sparing both traversed and deeper located healthy tissues. Thirdly, being charged, they can easily be formed as narrow focused and scanned pencil beams of variable penetration depth, so that any part of a tumour can accurately and rapidly be irradiated. Thus, a beam of protons, or light ions, allows highly conformal treatment of deep-seated tumours with millimeter accuracy.

This paper is organized as follows. In the first part Power supply specifications are given. In the second part the system topology is faced, while in the third one control design is described. Finally, in the last part, simulations results are reported.

Table 1: Specification for power supply.

| | |
|---|---|
| Three phase, 50 Hz input mains voltage | 15,000 V ± 10% |
| Maximum Output Current | 3,000 A |
| Maximum Output Voltage | ±1,600 V |
| Maximum Output Power | $>$ 5 MVA |
| Load Inductance | 199.1 mH |
| Load Resistance (cables included) | 79.24 mΩ |
| Current Setting and Control Range | 0.5 to 100% f.s. |
| Normal Operating Range (N.O.R.) | 0.5 to 100 % f.s. |
| Current Setting Resolution | $< \pm 5 \times 10^{-6}$ |
| Current Reproducibility | $< \pm 2.5 \times 10^{-6}$ f.s. |
| Current Readout Resolution | $< \pm 5 \times 10^{-6}$ f.s. |
| Residual Current Ripple (peak to peak) in N.O.R | $< \pm 5 \times 10^{-6}$ f.s. |
| Linearity Error $[(I_{set} - I_{out})/I_{set}]$ | $< \pm 5 \times 10^{-6}$ f.s. |
| Ambient Temperature | 0° to +40° C |
| Current Stability ($\Delta I/I_{set}$ over the normal operating range) | $< \pm 5 \times 10^{-6}$ |

## POWER SUPPLY SPECIFICATION

The CNAO synchrotron ring is equipped with sixteen bending dipole magnets, plus one off line dipole magnet used for magnetic field measurements. In order to drive the particles to the required energy, the magnets must follow a predetermined cycle (see figure 1). It consists of 7 parts: a starting bottom level (about the 5% of the maximum current level); a current/field ramp-up till the injection level, in a fixed time; a flat-bottom level (depending on the particle type) during which the particles are injected into the ring; a current/field ramp-up till the extraction level, in a fixed time; a flat-top level (not necessarily coinciding with the maximum current level and depending on the particular therapy cycle the patient must be subject to) during which the slow extraction takes place and the particles are extracted from the ring; a ramp-up till the maximum field/current value, for a correct magnet "standardization" (no particles are in the ring during this phase of the cycle); a ramp-down to the starting bottom level. To achieve the

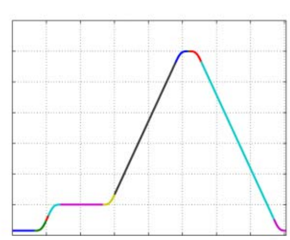

Figure 1: Magnets cycle.

above magnets behavior, the power supply has to satisfy some tight constraints. In particular, it has to track very high current references (M.O.C.=3000 A) with tracking error smaller than 5 ppm wrt f.s. (see table 1 for the complete power supply specification).

## TOPOLOGY

The stringent specification on CNAO synchrotron ring power supply includes two key requirements: high load current and small ripple and tracking error with respect to the specified reference.

The high requested current can be supplied by a thyristors-based power converter (in particular a twenty-four pulses SCR rectifier); nowadays, thyristors are the only controllable power device capable to work properly in so high current and voltage conditions. Unfortunately, they introduce high ripple in low load current conditions and their bandwidth is very small. Therefore, the small tracking error requirement cannot be satisfied using a twenty-four pulses SCR rectifier alone. The adopted solution consists in adding an Active Power Filter (APF) which cooperates with the 24-pulses rectifier in order to improve the tracking error capability of the system when the current reference is small or rapidly variable.

A first power converter design was characterized by a series connection between the APF and the 24-pulses rectifier. This choice required the addition of a transformer for the necessary APF DC-link electrical insulation: otherwise in the case of APF not inserted, the APF DC-link would be charged indefinitely. The series solution was soon discarded because the saturation of transformer complicated the control structure. In final power converter topology (fig. 2) a parallel connection has been preferred for the APF: in this way no additional transformer is needed and control structure is simpler. Moreover, using a suitable reconfigurable control, the parallel connected APF can be disconnected when necessary without mining the system stability.

In summary, the main components present in CNAO power supply topology are: a 24-pulse SCR-rectifier; an IGBT-based Active Power Filter; a digital control system (implemented on DSP and FPGA) controlling the 24-pulses and the APF output currents; a very accurate DCCT sensor (specifically designed for this application); a protection system (crow-bar) to discharge the load stored energy on the load itself.

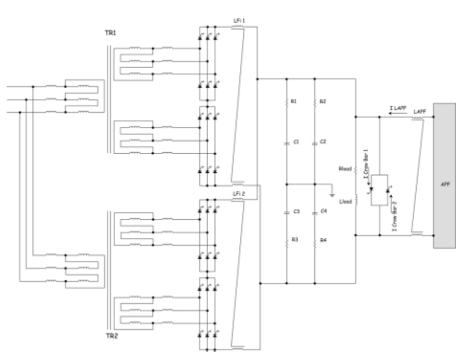

Figure 2: Topology of CNAO synchrotron power supply.

### *Twenty-Four Pulse Rectifier*

The twenty-four pulse SCR-rectifier is made up of two $\Delta_{ext}$-$\Delta_{ext}$-$\Delta_{ext}$ three-phase transformers, four six pulse thyristor bridges and a suitable passive low-pass filter. The primary windings of the transformers are parallel connected, consequently the nominal primary voltage is 15 kV, that is the voltage of medium voltage distribution network that power all the CNAO structure. The secondary windings are series connected. The requested output voltage of each secondary winding can be easily calculated given the maximum output voltage of the power converter $V_{max}$ and the voltage drops in transformers and HV/MV line $V_{linedrop}$. The specification's worst case has been considered, that is a -10% on primary nominal voltage: $V_{2(rms)} = 690$ V.

The low-pass filter dimensioning is performed to compensate the maximum load voltage ripple that is reached for a firing angle $\alpha = 90°$ of the thyristor bridge. In this case the output voltage waveform is a sawtooth with amplitude peak to peak of 976 V at frequency of 600 Hz. A LPF with resonance frequency of 145 Hz, $A_{db} = -24$ dB at $f = 1200$ Hz and $A_{db} = -35.5$ dB at $f = 2400$ Hz is chosen. The resulting inductors, capacitors and resistors parameters are: $L_{Fi1} = L_{Fi2}$= 3.2 mH, $C_1 = C_3 = 1.2$ mF, $C_2 = C_4 = 300\,\mu$F, $R_1 = R_3 = 0.7288\,\Omega, R_2 = R_4 = 25\,\text{m}\Omega$

### *Active Power Filter*

The APF is built by four modules series connected, each module being a four quadrant full bridge. The main stage of each module is a six pulses IGBT rectifier with a low pass filter whose resonance frequency is 70 Hz.

The sizing of DC-link capacitor is estimated assuming that the output current in the worst case can be approximated to a ramp with a slope of 267A/s for $T_{ramp} = 300$ ms. Hence, balancing the involved energies and considering the physical limitations of the components a DC-link capacitance of 15 mF is chosen.

As in twenty-four pulse rectifier, considering the voltage drop on APF lines $V_{linedrop}$, the nominal secondary output rms voltage can be calculated: $V_{2APF(rms)} = 346$ V

## CONTROL DESIGN

The aim of the control system design is to develop a closed loop control system suitable to be implemented on a DSP board. The design of the control system in the discrete time plays a fundamental role to satisfy the tight specification on CNAO power supply. To assure enough safety margin on the control system reliability, a sample period $T_s$=100$\mu$s has been chosen, i.e. a frequency of 10 kHz. Moreover, plants and regulators have been discretized using the ZOH method.

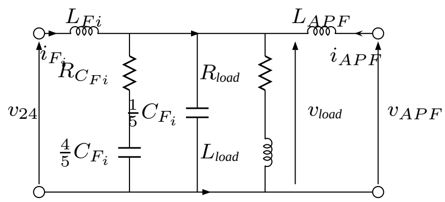

Figure 3: Simplified equivalent electrical circuit of the plant.

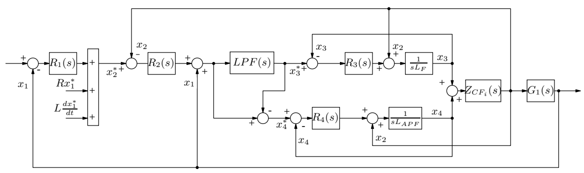

Figure 4: Structure of Cascade controller.

The design of a good control algorithm needs a previous modelling phase. In figure 3 a simplified electrical equivalent circuit of the plant is presented: from a control point of view the series connected dipole magnets constitute a single load with resistance (including cables) $R_{load} = 79.24$ m$\Omega$ and inductance $L_{load} = 199.1$ mH.

Denoting with $i^* = x_1^*$ the reference for the current running through the magnets, the goal of the CNAO controller is to generate the right controlling input $\mathbf{u}$ able to track $i^*$ with a maximum error equal to $\pm 0.015$ A.

The developed solution is a cascade controller, fig. . It is composed by three nested loops, with the inner one composed by other two parallel loops, that will be analyzed one by one in the next paragraphs.

## *Outer Loop*

The outer loop has to generate a correct reference $v_{load}^* = x_2$ for the intermediate loop when the reference $i^*$ is given and the tracking error is computed. The considered plant, obtained by a simple voltages balance on the load, is:

$$\dot{x}_1 = \frac{1}{L}(x_2 - Rx_1).$$

Since the controller has to track a linearly growing current reference it must contain a double integrator. The controller zeros have been placed to ensure a bandwidth as large as required by the current error requirements with the assigned current references. As the reference trajectory and the relation between the state variables $x_1$ and $x_2$ are well known, performance can be improved by adding a feedforward action, i.e. by adding to the output of $R_1(s)$ the sum $Rx_1^* + L\dot{x}_1^*$.

## *Intermediate Loop*

When the reference for the load voltage $x_2^*$ is given, next step is to compute the amount of current that has to be drawn from the 24 pulse rectifier and from the APF. Applying Kirchoff's current law we obtain:

$$x_s = x_1 + x_{ZCFi} = x_3 + x_4$$

where $x_{ZCFi}$ is the current flowing into the two branches in parallel with the load and the value the intermediate controller must generate, as $x_1$ is given.

## *Inner Loops*

The sum $x_s$ between the actual value of $x_1$ and the computed value of $x_{ZCFi}$ is the reference for the inner loop. However this current cannot be entirely supplied only by the 24 pulse rectifier due to its limited bandwidth . So, the separation between low frequency components, that will be tracked by the 24 pulse rectifier, and high frequency ones, that will be tracked by the APF, is required. This result is obtained by lowpassing the reference $x_s^*$ with a $1^{st}$ order low pass filter, having cut frequency at 70 Hz: The LPF(z) output will be $x_3^*$. Subtracting it from $x_s$, $x_4^*$ is given too.

## SIMULATIONS RESULTS

To test the topology and the adopted control strategies, extensive simulations have been carried out using Matlab and Simulink.

A Simulink model of the system has been implemented using SimPowerElectronics components initialized with parameters of table 1. The system has been tested with the whole set of current references, each one made up of constants or ramps connected by 5th order polynomial curves with no discontinuities in the first and second derivative (see fig. 1). For simulation purposes, these analog signals have been approximated to 100 KHz sampled signals (ten times the digital controller operating frequency).

All the tests have been performed both in nominal $V_{line}$ conditions and in critical $V_{line}$ conditions when input mains voltage can be either $110\%$ or $90\%$ of nominal value (see fig. 5 for 110% case). Moreover, stability in the case of APF not inserted, parameter uncertainties and quantization effect have been studied in order to test the behavior of the complete system.

Factory tests are scheduled before the end of 2006.

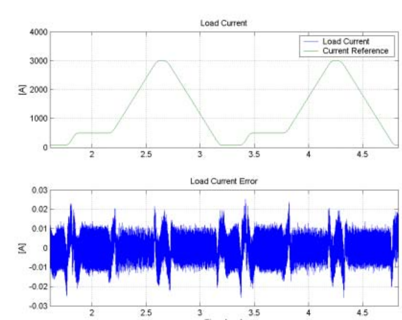


Figure 5: Total load current error, $V_{line}$ at 110%.