CNAO RESONANCE SEXTUPOLE MAGNET POWER CONVERTERS

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Abstract

The CNAO Resonance Sextupole Magnet Power Converter requirements for the Storage Ring of the CNAO Project are described together with performance and initial operating experience. In particular the achieved performances will be compared with the specification and the extensive modelling that was done during the design phase. Not only the tight required performances were emphasized during the design phase but also particular attention was put on reliability and minimization of the repairing time (MTTR). Some fundamental criteria, like component derating and standardisation, have also been taken into account during the component choice phase. All converters adopt the switching technology with full digital control and a common control interface, that, as for the other CNAO power converters, 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.

POWER SUPPLY SPECIFICATION

The sextupole is a special magnet of the CNAO synchrotron used to extract the particles from the main ring. It must stay at zero current during particles injection and acceleration, and ramp up to the specified current, different from cycle to cycle, in an overall time of about 50ms.

The corresponding current reference for the sextupole power supply is presented in figure 1.

The detailed power supply specification can be found in Table 1: it's worth to note the short rising time (25 ms) and the small tracking error (less than 50 ppm).

Table 1: Specification for power supply.

Three phase, 50 Hz input mains voltage	400 V $\pm 10\%$
Maximum Output Current	650 A
Maximum Output Voltage	$\pm$40 V
Maximum Output Power	$>$ 24kVA
Load Inductance (including cables)	3.26 mH
Load Resistance (including cables)	38.65 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	$< \pm 1 \times 10^{-4}$ f.s.
Current Reproducibility	$< \pm 5 \times 10^{-5}$ f.s.
Current Readout Resolution	$< \pm 1 \times 10^{-4}$ f.s.
Residual Current Ripple (peak to peak) in N.O.R	$< \pm 1 \times 10^{-4}$ f.s.
Linearity Error [(Iset - Iout)/Iset]	$< \pm 5 \times 10^{-5}$ f.s.
Ambient Temperature	$0°$ to $+40°$ C
Current Stability (.I/Iset over the normal operating range)	$< \pm 1 \times 10^{-4}$
Maximum ramp up/down time in the N.O.R.	25 ms
Maximum first ramp up time	150 ms

TOPOLOGY

The first proposed solution for the sextupole power supply used a Pulsed Power Supply Topology. It was composed by a Pulse Section (essentially a capacitor with thyristor bridge, resonant with the load inductance) and a Switching Section as regulator converter. After some considerations on the specification the Pulsed solution was abandoned. In fact, the same aim is achievable using a simpler and more standard switching topology.

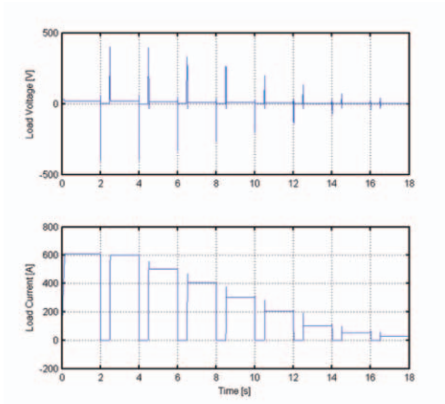

Figure 1: Load voltage and current during a treatment plan where the beam energy decrease cycle by cycle.

The adopted solution is composed by an input stage and an output stage (see figure 2). The input stage is made up of a $\Delta - Y$ transformer, a diode bridge and an input passive filter. The output stage is made up of two parallel connected IGBT full-bridges and an output filter. The load is parallel connected to the output filter.

Input Stage Dimensioning

The most important parameter to evaluate in the sizing of the input stage is the DC-link capacity. This value is estimated considering that the current drawn from the DC-link in the worst case is a ramp with a slope of 26000 A/s for $T_{ramp} = 25$ ms. Hence, balancing the involved energies and considering the physical limitations of the components, a DC-link capacitance $C_{F_i} = 165$ mF is chosen.

Then, in order to have the input filter resonance frequency at $f_0 = 22.5$ Hz, an inductance value of 300 μH is adopted.

Output Stage Dimensioning

Each full-bridge module is driven by a PWM signal at a frequency of 10 kHz. Since no phase displacement techniques are used, the resulting voltage ripple has an equivalent frequency of 20 kHz. The maximum current ripple is reached when the modulation index is equal to $\frac{1}{2}$. In order to maintain the ripple under the specification threshold the resulting low pass filter parameters are: $L_{Fumod1} = L_{Fumod2} = 60\mu$H, $C_{Fu1} = 320\,\mu$F, $C_{Fu2} = 80\,\mu$F, $R_{CFu} = 0.66\,\Omega$

CONTROL DESIGN

The aim of the digital control is twofold: make the power supply satisfy the specification (mostly the small rising time) and make the two output modules work in the same way by drawing the same amount of current from both of them.

Analyzing the electrical circuit made up of output filter and load, the following equations hold:

$$\begin{cases} V_1(s) - sL_{Fumod}I_1(s) = I_s(s)Z_b(s) \\ V_2(s) - sL_{Fumod}I_2(s) = I_s(s)Z_b(s) \end{cases}$$

where:

- V_i is the voltage input of the i-th module;
- I_i is the current flowing in the inductance of the i-th module;
- Z_b is the equivalent impedance corresponding to the parallel of output filter capacitor and load impedance;
- $I_s = I_1 + I_2$;
- $L_{Fumod1} = L_{Fumod2} = L_{Fumod}$.

Performing the change of coordinates

$$\begin{bmatrix} I_s \\ I_d \end{bmatrix} = T \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}, \qquad \text{where} \quad T = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

the following equations are obtained:

$$\begin{cases} I_s(s) = \dfrac{V_1(s) + V_2(s)}{sL_{Fumod} + 2Z_b(s)} = \dfrac{V_s(s)}{sL_{Fumod} + 2Z_b(s)} \\ I_d(s) = \dfrac{V_1(s) - V_2(s)}{sL_{Fumod}} = \dfrac{V_d(s)}{sL_{Fumod}} \end{cases}$$

As the real target of the control is I_{load}, considering the current divider the plant equations are:

$$\begin{cases} I_{load}(s) = \dfrac{1}{sL_{load} + R_{load}} \dfrac{Z_b(s)}{\frac{sL_{Fumod}}{2} + Z_b(s)} \dfrac{V_s(s)}{2} = \\ \qquad = H_{1,2}(s)\dfrac{V_s(s)}{2} \\ I_d(s) = \dfrac{1}{sL_{Fumod}} V_d(s) = H_d(s)V_d(s) \end{cases}$$

The regulator developed for $H_{1,2}(s)$ is a PI controller:

$$R_{1,2}(s) = k_p + \frac{k_i}{s}$$

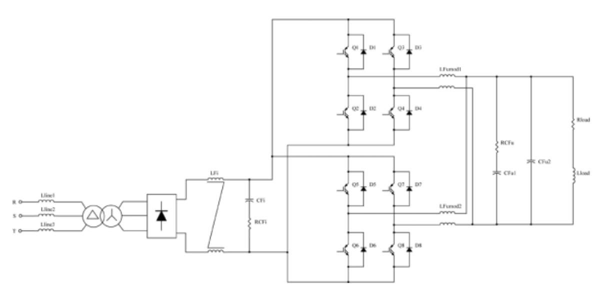

Figure 2: Topology of sextupole magnet power supply.

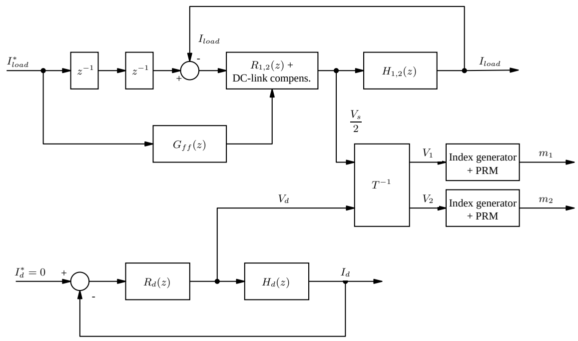

Figure 3: Structure of digital controller.

with $k_p = 7.08$ and $k_i = 7117$ while the regulator for $H_d(s)$ is a simple P controller with very slow dynamics

$$R_d(s) = 0.0562$$

Then, in order to implement controllers on a DSP board, both regulators and plants have been discretized using the ZOH method with a sample time of 100 μs, i.e. a frequency of 10 kHz. The control action is performed by generating appropriate PWM indexes that are calculated from V_s and V_d with a suitable change of base.

The overall performances can be improved by means of the following feedforward action based on the load discretized model inversion.

$$G_{ff}(z) = 32.6193\,\frac{z - 0.9988}{z}$$

Since the relative degree of the controlled system is 2, the digitalized current reference is 2 samples delayed in order to synchronize it with the feedforward action.

Final improvements on the control system are the *DC-link voltage compensation*, introduced to avoid drawing more current than available on the DC-link, and a combination of PWM and PRM (Pulse Repetition Modulation) techniques to increase the accuracy of digitalization.

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. 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 figures 4, 5 and 6 for 90% case).

Delivery of Sextupole magnet power supply is scheduled for July 2006.

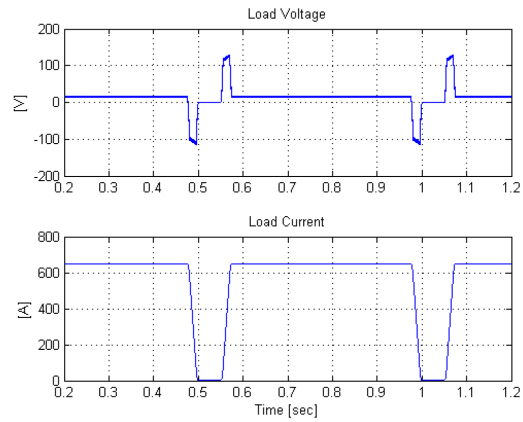

Figure 4: Load voltage and current V_{line} at 90%.

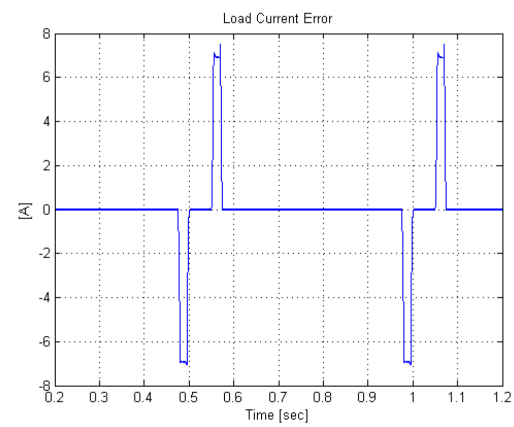

Figure 5: Load current error, V_{line} at 90%.

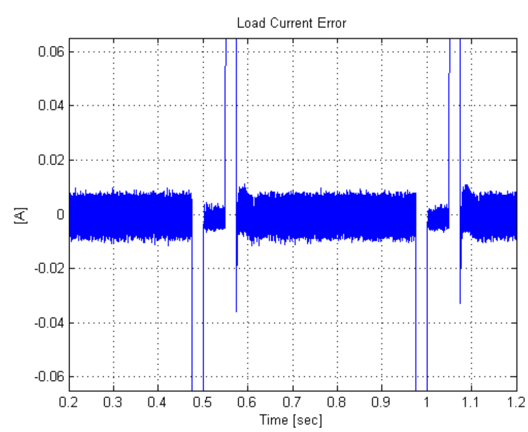

Figure 6: Load current error (zoom), V_{line} at 90%.