THE ITALIAN HADRONTHERAPY CENTER (CNAO): A REVIEW OF THE POWER SUPPLY SYSTEM FOR CONVENTIONAL MAGNETS

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Abstract

A hadron (Carbon/Proton) medical centre based on a synchrotron accelerator dedicated to the cure of deep tumours is under construction in Pavia (Italy) under the joint responsibility of CNAO (Centro Nazionale di Adroterapia Oncologica) and INFN (Istituto Nazionale di Fisica Nucleare). This paper describes the power supply system, made up of nearly 200 units designed by LNF, and whose converters for the synchrotron ring and related low, medium and high energy transfer lines are now under construction by the major Italian companies. The requirements and electrical characteristics of the power supplies will be reported describing the most interesting topologies that satisfy the requested performances together with the main features of each power supply topology.

Synchrotron dipoles, quadrupoles, sextupoles, steering magnets and resonance sextupole power supplies have tight characteristics with respect to precision class (current resolution, residual ripple, short-long term stability, etc.) that range from ±5 ppm to ±1000 ppm, fast dynamical response with bandwidth up to some hundreds hertz, high power from tens of kW to many MW and output current ranging from hundreds of Amps to 3 kA.

INTRODUCTION

The CNAO project is a synchrotron accelerator where heavy Carbon ions or Protons are injected at a fixed energy through Low-Energy and Medium-Energy Beam-Transfer lines (LEBT and MEBT); the particle beam is accelerated and then extracted to be driven (by High-Energy-Beam-Transfer line HEBT) to the treatment room where the patient has to be cured. To maximize the number of patients per year the acceleration cycle shape has been optimized allowing the energy variations from injection to extraction in 0.5 sec. Moreover, the relatively low energy of the beam and the stringent requests on the energy level accuracy of the extracted beam, have lead to the design of very unique power supplies (PSs).

A summary of PSs characteristics can be found in Tab.1. The major part of PSs is under construction by two Italian firms: EEI is building the synchrotron quadrupoles and chromaticity sextupoles PSs, and OCEM all the other PSs of the synchrotron and transfer lines. The PSs have been tightly specified by LNF. The specifications have been written out taking into account many requirements:

- Achieving high reliability to increase life time and MTBF by suitable component over-sizing or PSs redundancy.
- Selection of PSs topology and definition of major technical aspects to be followed by the firms.
- Reduction of topologies number to standardize the system and reducing spare parts.
- Detailed description of technical and precision class requirements.
- Advanced local control facilities to be able to perform meaningful tests during maintenance and reducing repairing time of PSs.

A first set of detailed simulations of the most critical PSs have been also carried out by LNF to investigate their feasibility [1]. All the PSs have then been carefully simulated by the firms.

POWER SUPPLIES REQUIREMENTS

The major characteristics of the PSs can be found in Tab.1. As can be seen the output currents range from 30 A to 3000 A and the output voltage from 15 V to 1600 V. In spite of this relatively wide spread of values the PSs topologies have been reduced to only four as can be seen also in Fig.1.

The most critical PSs are the ones for the synchrotron dipoles [2] and quadrupole magnets. Their requirements in terms of precision class – i.e.: stability, accuracy, output current ripple – and linearity are about a factor ten more stringent than what usually requested for other synchrotron accelerators. Moreover, they are requested to perform in the same way during the fast energy variations of the synchrotron.

To achieve precise regulation and fast dynamic response Switch Mode Power Supply Active Filter (SMPS-AF) have been implemented in the high-power bending dipole PS and in the high-current PSs of the HEBT line.

Quadrupoles PSs are SMPS characterized by a high power density; to fulfil the tight precision requirements they are implemented with a power-mosfets linear regulator system. As reported in Tab.1 all the PSs are bipolar in voltage to discharge the magnet energy in the proper way and in a short time. This requirement has heavily conditioned the design of the PSs.

Description	Voltage [V]	Current [A]	Precision Class [ppm]	Linearity Error [ppm]	Number of PSs	Topology	Circuit Inductance [mH]	Circuit Resistance [mohm]
SYNCHROTRON								
Bending Dipoles	±1600	3000	±5	±5	1	Thyristors+ SMPS-AF	210.29	81.77
Quadrupoles	±160	650	±5	±5	4	SMPS	36.71	152.24
Resonance Sextupole	±130	650	±100	±50	2	Pulsed SMPS	3.27	26.28
Chromaticity Sextupoles	±60	650	±100	±50	3	SMPS	6.54	52.56
Horizontal Correctors	±30	±30	±1000	±250	11	Linear	84.87	462.70
Vertical Correctors	±30	±30	±1000	±250	9	Linear	9.75	92.00
					30			
LEBT								
Dipole 90º	±35	300	±50	±50	3	SMPS	107.00	150.00
Dipole Y 30º	±30	±30	±1000	±250	2	Linear	168.40	441.50
Dipole 75º	±35	300	±50	±50	1	SMPS	6.87	43.22
Correctors (both planes)	±15	±60	±1000	±500	20	Linear	0.08	145.07
Quadrupoles	±35	300	±50	±50	12	SMPS	0.80	22.36
					38			
MEBT								
Dipoles	±35	300	±50	±50	3	SMPS	61.60	65.90
Quadrupoles	±20	150	±50	±25	10	SMPS	23.86	32.30
Correctors	±15	±60	±1000	±500	16	Linear	9.73	73.15
					29			
HEBT								
Dipoles	±110	3000	±25	±25	11	Thyristors+ SMPS-AF	12.37	4.81
Quadrupoles	±65	350	±50	±25	38	SMPS	48.30	51.36
Correctors	±30	±150	±1000	±500	38	Linear	9.40	94.78
					87			
TOTAL NUMBER OF PSs					**184**			

Tab.1: Power Supplies Characteristics

Another interesting PS typology is the one adopted for the Resonance Sextupole PS [3]. The resonance sextupole is a magnet that allows the extraction of the particles from the synchrotron ring and drives them into the HEBT line. For this purpose it must reach the set current, different for any energy level, in about 25 ms. This PS is an SMPS that does not use large resonant capacitor as in conventional pulsed PSs. The implemented topology achieves fast dynamic response and valuable reduction of size using a relatively small electrolytic capacitor bank providing ideal voltage source for the DC-link and high-power IGBTs H-bridge connected to perform waveform regulation during ramp and DC operation.

Steering magnets PSs have linear regulation to provide optimum zero-crossing and true bipolar output current. They have been built in cabinets having a common part and two to four independent ways each, reaching a relatively high power density. They also have valuable characteristics with respect to dynamics; they must not only track the standard reference cycle but have to reproduce an additional bump during particles injection for beam scraping purposes. Such a function requires a PS with several kHz bandwidth.

The reference current figure of each cycle will be given to the PSs in two different ways:

1. Each Synchrotron PS will be equipped with a National Instruments electronics rack that generates a digital data sequence of the sampled cycle with a frequency varying from 10 kHz to 50 kHz according to the PS requirements, allowing fine tuning and control.
2. Transfer Lines PSs will receive digital words in which the basic parameters for cycle description are coded; different segments of the cycle will be performed using suitable timing signals (i.e.: start acceleration ramp, start hysteresis cycle,…).

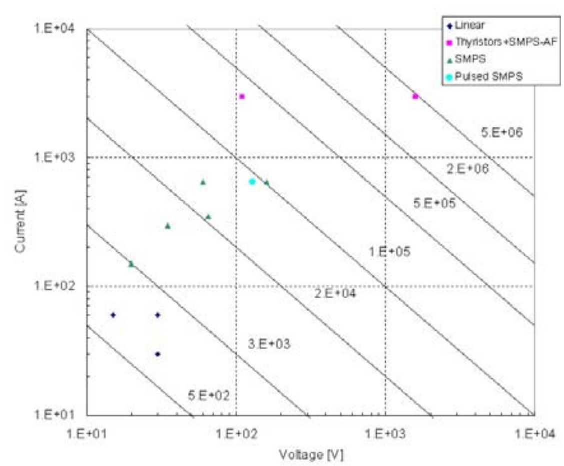

Fig.1: PSs topologies and electrical characteristics

HOW TO GET HIGH PERFORMANCE

To achieve the high performance formerly described, several expedients have been adopted. All power supplies have been carefully simulated by Matlab/Simulink® and PSIM® software by the firms. This allowed the optimization of control loop parameters taking into account, as far as possible, devices non-linearity (sensors, electronic elements, mains perturbations,…) and circuit parameter uncertainties.

The cycle shape has been optimised with the help of simulations. It has been found that power supply tracking errors can be reduced by building the cycle with linear ramps and polynomial interconnections. The coefficients of the polynomials have been calculated imposing continuity conditions at the extreme points and setting to zero the first and second derivatives. Fifth-order polynomials are sufficient to drastically reduce transient errors.

High precision DCCTs have been adopted for almost all the PSs. In particular the PSs for synchrotron dipoles and quadrupoles and for HEBT dipoles, are equipped with HITEC® DCCTs and burden resistors that exhibit excellent linearity and power coefficient. This is a fundamental parameter since the synchrotron is a cycled machine, and one important problem is the thermal stabilization of the burden resistor. In some applications the dissipated power on this component has been strongly reduced. For example, for the bending dipoles PS the voltage across the burden resistor has been reduced to only 100 mV for 3000 A. In many PSs the burden resistor has been thermally stabilized by water cooling (32±2°C).

An additional winding has been foreseen on the measuring head of many DCCTs to calibrate them and to reduce linearity errors. The synchrotron dipoles PS is equipped with two DCCTs to provide a spare and an out of loop independent measuring point.

All the electronics cabinets will be air conditioned to provide constant temperature and optimal component working point.

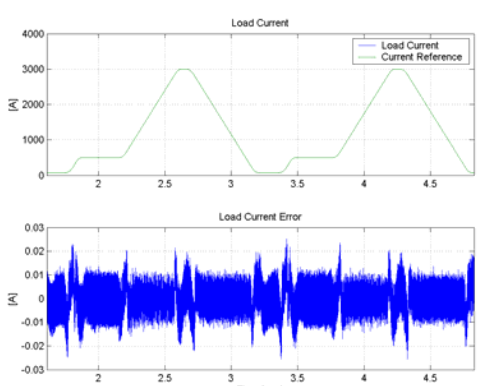

Fig.2: Typical load current shape and error of synchrotron dipoles PS

The layout of the cabinets has been tightly designed in collaboration with the firms with particular attention to proper arrangement of bus-bars, to the symmetry of the component positioning, to the decoupling of AC and DC elements, to the maintenance ease and accessibility, etc.

Fully digital control of PSs has been required. OCEM will adopt the digital control boards developed at PSI (Paul Scherrer Institute) also used in DIAMOND accelerator PSs developing the firmware and implementing the control algorithms; EEI will use proprietary digital control boards that make use of both DSPs and high-speed FPGA.

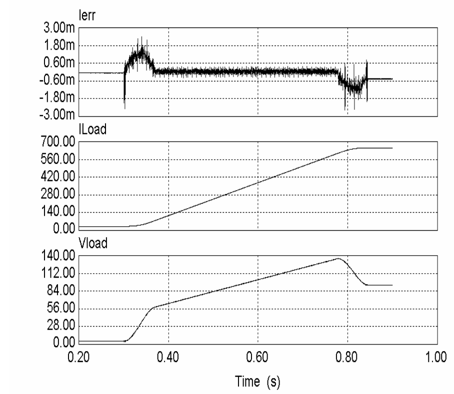

Fig.3: Typical load current shape and error of synchrotron quadrupoles PSs

To increase synchrotron PSs performances the cycle reference points will be provided to the PSs three points in advance to allow suitable calculations to the digital processors.

Typical current reference cycles and tracking errors of the simulations of synchrotron dipoles and quadrupoles PSs are shown in Figs.2-3. It can be seen that within the approximations so far described the specification requirements are fulfilled.

CONCLUSIONS

The complete PS system of a synchrotron accelerator for medical purposes has been presented in the paper. PSs requirements have been summarized highlighting the most challenging ones. Major technical aspects of the most critical PSs that will determine the achievement of high-performances, have been analysed as well.

The hadrontherapy center is now under construction in Italy at Pavia site and PSs are going to be completed by the firms in a few months. Simulations and preliminary measurements on the first prototypes show promising results.

REFERENCES

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