DIGITAL INTERNAL MODEL CONTROL OF HIGH-PRECISION POWER SUPPLY FOR PARTICLE ACCELERATOR MAGNETS

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Abstract: The paper presents the control of a power supply feeding a quadrupole magnet of a booster synchrotron. The supply equipment is based on a switching architecture where current sharing and interleaving techniques are adopted to minimize the voltage/current ripple. Internal model principle is exploited in the control design to guarantee extremely accurate tracking of the sinusoidal current reference for the quadrupole magnet. PWM-based digital solution is adopted instead of analog hysteresis one to avoid unpredictable behaviors of the current ripple and to allow a simple and reliable implementation of the proposed controller. Extensive simulations confirm satisfactory performances.

Keywords: Power Supplies, Digital Control, Lumped Constant Model, Model-Based Control, Magnetic Fields.

1. INTRODUCTION

Recent developments, based on the usage of synchrotron radiation in biology, medicine, chemistry, electronics, nano-technology, etc. have promoted the design and construction of a number of third generation light sources worldwide at the intermediate energies of 2.5-3.5 GeV (Tsakanov *et al.*, 2001; Suller, 2002). A synchrotron light source is a ring-shaped microscope that produces extremely intense and coherent light beams that can penetrate deep inside all kinds of matter. Synchrotron light is emitted when charged particles travelling close to the speed of the light are accelerated by a magnetic field perpendicular to their paths. The field is generated by multi-pole magnets (Marks *et al.*, 2002*a*; Marks *et al.*, 2002*b*) as dipoles, quadrupoles and sextupoles which act like lenses, focusing and defocusing the beam into a narrow thread of particles. The requirements on the magnetic field, and therefore on the current of the magnets, are very high: a short term stability down to 10 ppm (part per million) is usually required (Marks *et al.*, 2002*a*; Jenni *et al.*, 2002).

Different designs have been proposed for magnet power supplies (Griffiths *et al.*, 2002; Jenni *et al.*, 2002) both in terms of power supply topology and current control. For what concern the former the solutions proposed to power a fast-cycling synchrotron were the traditional "White Circuit" and a "Direct Connection" option (Marks and Poole, 1996). The white circuit use an inductive/capacitive resonant circuit and is utilized to power the booster of BESSY II, Berlin, DESY II, Hamburg, and ESRF, Grenoble. The direct connection option consists of a bare connection between the load and the local electricity distribution by means of a transformer but, because of its large costs, it is not considered an attractive choice. Nowadays the most promising topology for power supply is surely the so called "Switch-Mode" solution (Carwardine and Lenkszus, 1999; Marks *et al.*, 2002*c*). In fact, the availability of fast high-power switching devices has increased dramatically, making possible to consider this type of topologies for high power applications, as never do before. For example, prompted by the successful introduction of a switch mode system at the Swiss Light Source (Joho *et al.*, 1998), the use of this type of circuit with an electrolytic capacitor energy storage system is strongly favored by DIAMOND Ltd Company for its Booster dipole supply (Marks *et al.*, 2002*c*).

Another important topic affecting the power supply performances is the control strategy. In the past the traditional solution for the current control was based on an analogue loop using a standard PID controller (Pett *et al.*, 1996). However nowadays the digital regulators offer several advantages that make them attractive, such as the possibility of more advanced and complex control methods (Carwardine and Lenkszus, 1999; Pett *et al.*, 1996), less susceptibility to parameter variations from thermal effects and aging, and less sensitivity to noise. A major advantage of the digital regulator is the possibility of changing regulator dynamic behavior through software changes. An example of digital regulator is proposed in (Jenni *et al.*, 2002) where a PI controller ensures satisfactory results. In (Hara *et al.*, 1981) repetitive control technique is adopted to cope with periodic current references.

Aim of this paper is to present an advanced control strategy for a particular kind of quadrupole magnet power supplies. The case of the booster quadrupole magnet power converter of the DIAMOND "third generation" synchrotron radiation facility under construction at the Rutherford Appleton Laboratory in Oxfordshire has been considered (www.diamond.ac.uk). The power supply adopted in this case-study exploits a switch mode solution and current sharing topology. The latter, combined with an interleaving switching coordination strategy (Batchvarov *et al.*, 2000) and

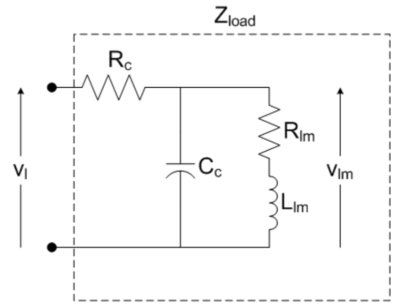

Figure 1. Electrical lumped scheme of the magnet.

well-designed output filter, allows for minimization of the current ripple, in compliance with the very stringent requirements.
The current waveform which has to be imposed in the quadrupole magnet is given by the sum of a constant term and a sinusoid of fixed frequency. Very high accuracy has to be guaranteed in tracking the desired current reference. An internal model based control technique has been adopted to tackle this requirement. Digital implementation of the proposed solution and standard PWM technique to generate the voltage required by controller have been adopted to guarantee the interleaving switching coordination. This approach is preferable with respect to analog hysteresis-based current control method which could lead to unpredictable switching behavior, impairing the benefits of interleaving technique (U-97, n.d.; Batchvarov *et al.*, 2000).

The paper is organized as follows. In Section 2, the overall system is described: the magnet model, the required current trajectories and accuracy are reported; the structure of the adopted power supply is described and the feature of current sharing topology with interleaving technique are presented. In Section 3, motivations which lead to the adopted control design approach are deeply discussed and the proposed control solution is presented. Simulation results are presented and discussed in Section 4.

2. SYSTEM DESCRIPTION

2.1 Lumped Magnet Model and Power Supply Structure

The hardware considered can be conceptually split in two blocks: the magnet load and the power supply. The former is the main load and has to be modelled, the latter has the objective to drive the magnet current satisfying the high stability required.

Lumped Magnet Model. The load consists of a set of quadrupole magnets connected each other by means of cables making, from the power supply point of view, an unique magnet. Magnets are made by laminated iron cores. These together with flux diffusion into the copper windings involve a frequency dependency of the inductance and resistance load. Moreover, in order

Table 1. Specifications for Booster Quadrupole Magnet Power Converter.

Type of power converter required	two quadrant (voltage bipolar, current unipolar)
Minimum waveform cycle time	$200ms$
Typical waveform	Biased sine wave
Maximum peak current	$200A$
Current control range	$2-200A$
Current accuracy with respect to the reference	$< \pm 50$ ppm of the rated current $= \pm 10mA$
Current ripple with the magnet load	$< \pm 10$ ppm of the rated current $= \pm 2mA$

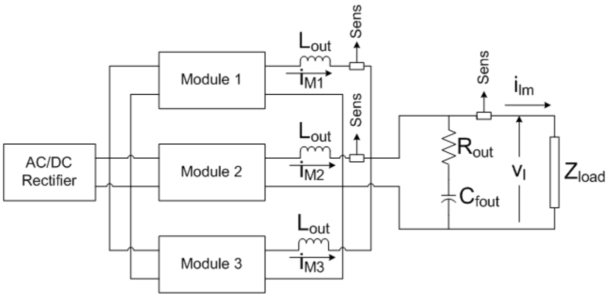

Figure 2. Power supply scheme.

to minimize stray magnetic fields the cables frequently run close to the magnets involving a capacitive effect.

For a good control design a lumped load model representing the aforementioned effects is highly desirable. The scheme of Fig. 1 is the electrical magnet model assumed and R_{lm}, L_{lm}, R_c and C_c stand for resistance and inductance of the magnet and resistance and capacitance of the cable respectively.

The specifications about quadrupole magnet current, depicted in table 1 highlight a current reference that is biased sine wave, with a reference frequency of $5Hz$ and with a continuous component. The current flowing through the magnet have to be always positive. For this type of application is easy to envisage that the current reference changes with low dynamics during working. This assumptions strongly condition the design of the control bandwidth that is around $50Hz$. This choice allows a good truck of the current both in steady-state and in transitory-state. The dominant effect at such frequencies is the one of L_{lm} while the effects of the other elements come out at the high frequencies. Therefore, when control design will be considered, only L_{lm} will be taken into account and damping of spurious effects coming out at the high frequencies will be ensured by internal model.

Power Supply Structure. The structure of the power supply is depicted in Fig. 2. It's consists of: an AC/DC rectifier, three modules and an output filter connected to the magnet load described above and here indicated with Z_{load}.

The AC/DC rectifier has the objective of feeding the connected loads that, in this case, are the three modules. In this block the power can flows only towards

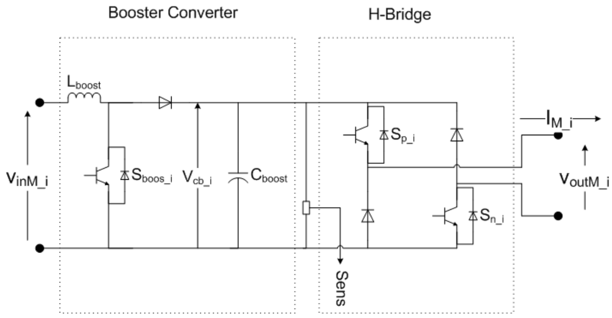

Figure 3. Structure of the Modules. The i stands for the module number.

the modules, because of employing of diode bridges inside the structure.

The three modules represent the heart of the topology chosen. Every module consists of the series of a booster converter and a two quadrant H-bridge as depicted in Fig. 3. Since it is required to track a biased sinusoidal current on the load reactive power is exchanged with the load. On the other side, since AC/DC rectifier is unidirectional, no power can flow back to the line. Reactive power has to exchanged between load and H-bridge: as a result, the voltage of C_{boost} of the booster converter is time-varying, hence a compensation has to be provided in the output stage controller. Suitable control of the booster stage is needed to drawn the required active power from the mains minimizing the harmonic distortion. The other part of the modules is the H-bridge. It is a classical two quadrant bridge where V_{outM} can be both positive, negative and null while I_M only positive. The adopted PWM carrier frequency is $f_{PWM} = 7.5KHz$. This topology was preferred at the full bridge four quadrant topology because it ensure good performances the same and its electronics circuitry is less complex.

The last part of the power supply is the output filter that is constituted by the three L_{out} that are conceptually connected in parallel, R_{out} and C_{out}. The elements of the output filter are designed with the objective to damp the harmonics at the high frequencies and to not adversely affect the $5Hz$ component of the current. Moreover the L_{out} are designed in such manner that the resulting current ripple of I_{M_i} is low enough to ensure a continuous conduction of the diodes. This filter is oversized with respect to the current ripple requirement of table 1 since it is employed also for the reduction of the voltage ripple applied on the load.

2.2 *Consideration on the adopted structure*

The structure adopted for the power supply is based on a current sharing scheme. When interleaving technique is employed with this kind of topology improved performances can be ensured with respect to the case of an unique module power supply. In the interleaving technique the modules are driven in the same way in terms of amplitude but the switch commands are shifted in phase of an amount equal to $2\pi/N$ where N is the number of modules taken into account (Chang, 1995; Zhou *et al.*, 2000; Batchvarov *et al.*, 2000).

The employing of current sharing technique yields important benefits:

- When the power supply is split in N modules also the correspondent output current is split in N contributions feeded by the various modules. So also the correspondent ripple in every legs is divide by N.
- The combination of optimal interleaving technique and current sharing topology yields an equivalent voltage ripple reduced of N times as for the current in the single legs. Moreover the equivalent frequency ripple that is possible to appreciate at the input of the output filter is Nf_{PWM}.

It's worth noting that due to the asymmetry among the modules the current balance is not intrinsically guarantee and a suitable control have to be provided.

3. INTERNAL MODEL CONTROL

In this section the proposed solution to control the current supplied by the power converter is described. The adopted approach is strictly related to the high accuracy requirements and to the selected current sharing topology with interleaving coordination of the converters switchings as enlightened in the following. The control of the booster stage of the modules of the power supply is not considered in this work.

3.1 Motivation of the proposed approach

According to the converter topology and the accuracy requirement on the supplied current, the control objective is twofold:

(1) the current flowing in the load magnet has to track asymptotically the biased sinusoidal reference with a steady-state error lower than $10mA$, no particular requirement on the convergence rate is present;

(2) currents drawn from the branches of the proposed topology have to be equal.

The control approach definition is mainly related to the first control objective which can be pursued by means of two control strategy:
- using an high-gain/large-bandwidth controller which guarantees sufficiently large gain at the frequencies where the harmonic content of the reference is relevant (0Hz, 5Hz);
- using an internal model based controller which contains the dynamic model of the reference guaranteeing asymptotic perfect tracking even with quite narrow bandwidth (this is admissible since no requirement on the convergence rate is present).

From a practical viewpoint, the first solution is generally realized using an analog hysteresis current controller for each branch of the proposed structure and a supervising controller (in this way also the second control objective is guaranteed imposing equal references to the branches). This solution is basically a sliding mode control method exploiting the "switching nature" of the power converters, hence it is very effective in terms of tracking. Nevertheless, it is well known that hysteresis solutions could generate unpredictable converter switching sequences, impairing interleaving coordination between the branches and leading to low frequency current ripples with relevant amplitudes. Some solutions have been presented in literature to deal with this unpleasant phenomena (U-97, n.d.; Batchvarov *et al.*, 2000), but no formally-proven, simple, robust and reliable solution seems available when varying current references are considered. Hence hysteresis control of the branches could violate stringent ripple requirements of the considered case-study and should be discarded.

Remaining in the framework of high-gain/large bandwidth controller, analog PID could be used in combination with standard PWM technique to guarantee predictable current ripple, but, as stated in Introduction, analog linear controllers are not very reliable. A digital implementation of such solution can be pursued, but owing to the high gain requirements a large bandwidth controller will result (unless complicated lag network are added) and very small sampling time will be necessary. Hence, as a final result, the second solution is clearly preferable since it guarantees excellent performances in terms of asymptotic tracking, it is simple (no compensation network is required) and suitable for digital implementation and small sampling time are not needed since the resulting bandwidth can be kept very narrow.

3.2 System model and Control Design

The simplified Linear Time-Invariant (LTI) model representing the basic behavior of power supply combined with the load magnet and adopted in the control design is the following:

$$\begin{aligned}
L_{out}\dot{i}_{M1} &= v_{outM1} - L_{lm}\left(\dot{i}_{M1} + \dot{i}_{M2} + \dot{i}_{M3}\right)\\
L_{out}\dot{i}_{M2} &= v_{outM2} - L_{lm}\left(\dot{i}_{M1} + \dot{i}_{M2} + \dot{i}_{M3}\right)\\
L_{out}\dot{i}_{M3} &= v_{outM3} - L_{lm}\left(\dot{i}_{M1} + \dot{i}_{M2} + \dot{i}_{M3}\right)\\
i_{lm} &= i_{M3} + i_{M3} + i_{M3}.
\end{aligned} \tag{1}$$

High frequency dynamics related to capacitor C_{out} and parasitic elements of the magnet are neglected in (1) since their effects are not relevant in the control frequency range and steady-state tracking robustness will be guaranteed by the internal model approach.

Table 2. Parameters for Booster Quadrupole Magnet Power Converter.

Parameters	Values	Units
R_{lm}	0.496	Ω
L_{lm}	105	mH
R_c	0.187	Ω
C_c	16	nF
R_{out}	12.5	Ω
C_{out}	350	μF
L_{out}	10	mH

According to the control objectives the following coordinate transformation is defined

$$\begin{bmatrix} i_{lm} \\ i_{d1} \\ i_{d2} \end{bmatrix} = \mathbf{T} \begin{bmatrix} i_{M1} \\ i_{M2} \\ i_{M3} \end{bmatrix}, \begin{bmatrix} u_{lm} \\ u_{d1} \\ u_{d2} \end{bmatrix} = \mathbf{T} \begin{bmatrix} u_{M1} \\ u_{M2} \\ u_{M3} \end{bmatrix}, \mathbf{T} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \tag{2}$$

and the resulting model is

$$\begin{bmatrix} \dot{i}_{lm} \\ \dot{i}_{d1} \\ \dot{i}_{d2} \end{bmatrix} = \begin{bmatrix} \frac{1}{3L_{lm}+L_{out}} & 0 & 0 \\ 0 & \frac{1}{L_{out}} & 0 \\ 0 & 0 & \frac{1}{L_{out}} \end{bmatrix} \begin{bmatrix} u_{lm} \\ u_{d1} \\ u_{d2} \end{bmatrix}. \tag{3}$$

In this new reference frame the model of the relevant current component is completely decoupled. According to previous subsection, the control voltages u_{lm}, u_{d1} and u_{d2} are designed to control i_{lm}, i_{d1} and i_{d2} respectively, exploiting the internal model principle and assuming a digital implementation. The adopted sampling time is $0.533ms$ ($f_s = 1875Hz = 1/4 f_{PWM}$) and the controllers transfer functions in Z-domain are

$$\frac{u_{lm}(z)}{i^*(z)-i_{lm}(z)} = \frac{0.2(z-0.9975)(z^2-1.98z+0.9803)}{(z-1)(z^2-2z+1)} \tag{4}$$

$$\frac{u_{di}(z)}{i_{di}(z)} = -\frac{0.0028(z-0.9975)(z^2-1.98z+0.9803)}{(z-1)(z^2-2z+1)}, i = 1,2 \tag{5}$$

where $i^*(z)$ is the sampled reference for the magnet current. Note that the poles of the proposed regulators correspond to the discrete-time model of the exosystem generating constant and 5Hz-sinusoidal signals.

Remark 1. The control actions u_{d1} and u_{d2} should be equal to zero in ideal conditions, in fact current balancing control is inserted only to cope with asymmetries of the power modules.

Remark 2. The voltage commands imposed by the controllers have to be translated in duty cycle requirements for the interleaving PWM controller of the converters H-bridge switches. This task is quite critical since, as stated in Section 2, the v_{cb_i} has relevant oscillations owing to exchange of reactive power with the load magnet.

4. SIMULATIONS RESULTS

In simulations tests the overall system model has been considered (i.e. the output filter, the parasitic elements of the magnet and the converters switches has been taken into account). The requirements of table 1 and the parameters of table 2 are assumed. The results proposed refer to a simulation in full output power (i.e. the reference current is the maximum allowable). The load current i_{lm} and the current reference with the corresponding error are shown in Fig. 4. Thanks to the internal model based control the tracking of the current is very good. Error is kept below the admissible limit for the current error that is $10mA$. The current ripple is shown in Fig. 5. It is appreciable that the requirement of a ripple equal or less $2mA$ is satisfy. Fig. 6 depicts the currents of the three modules

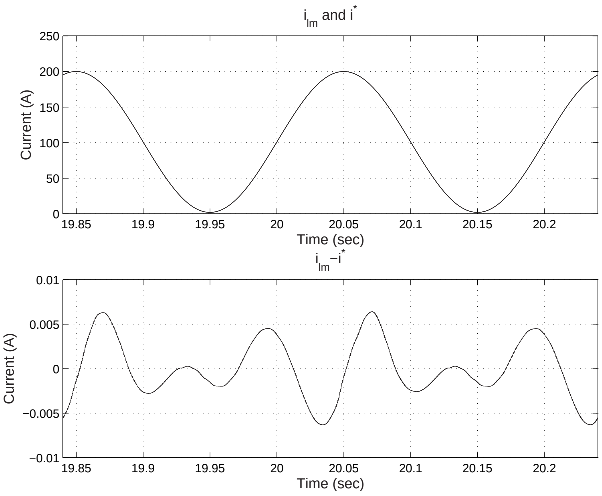

Figure 4. Magnet current, reference current and current error.

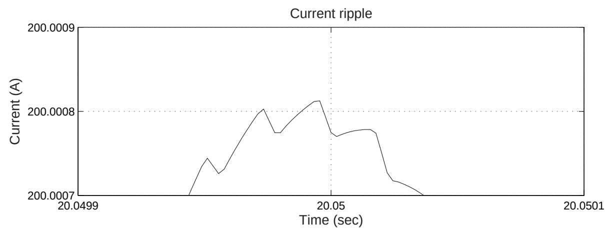

Figure 5. Current ripple.

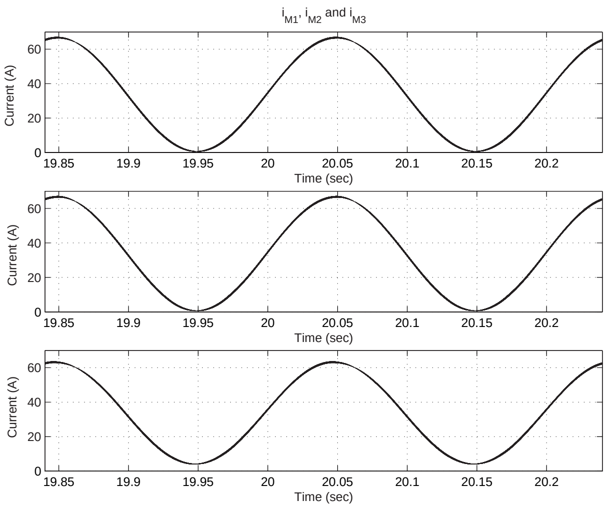

Figure 6. Currents of the modules.

considered. It possible to appreciate that currents i_{M1} and i_{M2} are quite similar. The current i_{M3} is slightly different since it is not directly sensed and a small current is drawn into C_{out}.

5. CONCLUSIONS

Internal model principle has been exploited to achieve high accuracy control of the current injected in the booster quadrupole magnet of the DIAMOND synchrotron. Digital implementation of the proposed controller and interleaving PWM techniques guarantee predictable switching behavior and very small load current ripple complying with the DIAMOND project requirements. Simulation results shown the effectiveness of the presented solution. In future works the controller adopted for the boost stages characterizing the adopted power supply architecture will be presented. Experiments will be performed during factory and site acceptance tests of the considered equipment.

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