

# INNOVATIVE DESIGN OF THE FAST SWITCHING POWER SUPPLIES FOR THE SOLEIL EMPHU INSERTION AND ITS FAST CORRECTORS

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## Abstract

A new electromagnetic/permanent magnet helical undulator has been designed and is under commissioning at SOLEIL. For a fast switching of the photon polarization, it requires a power supply able to switch between  $\pm 350$  A within 50 ms, without any current overshoot and with a good current precision over the full scale (100 ppm of the nominal current). The in-house design is based on two switched-mode inverters with interleaved commands. Combined with a regulation scheme using sophisticated algorithms, such a design enables to reach a high control bandwidth, permitting fast transitions. This fast and accurate system needs well performing digital control electronics. We chose the digital control cards developed at the Paul Scherrer Institute (Villigen CH) for the SLS (Swiss Light Source). The components, power assemblies and electronic cards were designed and assembled together at SOLEIL. This paper will present the main lines of this development. The design of the fast power supplies needed for the corrector magnets of this insertion device will also be presented.

## INTRODUCTION

A new electromagnetic/permanent helical undulator, with a 65 mm magnetic period is under development at SOLEIL for providing a rapid switching of the photon polarization required to perform dichroism experiments [1]. The EMPHU uses permanent magnets for the horizontal field and coils around poles for the vertical one. To feed these coils, a 4-quadrant power supply is needed with a maximum current of 350 A, and a polarity switching time shorter than 50 ms. The current reference of this power supply will have a trapezoidal shape with rounded corners. The data acquisition in the beamline will be triggered during the flat section of the trapeze where a 100 ppm precision is required. The repetition rate will extend between DC and 5 Hz. A set of 8 corrector power supplies is also needed to feed the correction coils used to compensate any beam closed orbit distortion consecutive to transitions of the main magnetic field. These power supplies, rated between 10 A and 20 A, should provide at least a response as fast as the main power supply and should be synchronised with it in order to keep the horizontal and vertical transition effects as low as possible.

## MAIN POWER SUPPLY DESIGN

The main power supply has been designed in several steps. This follows from an inaccurate modelling of the load, which initially had been assumed to be of type RL, with  $R = 130$  m $\Omega$  and  $L$  between 4 and 8 mH depending

on the delivered current. But at the time of the power tests of the undulator, its true equivalent circuit revealed to be of type R-Parallel R-L, as shown in Fig. 1(a).

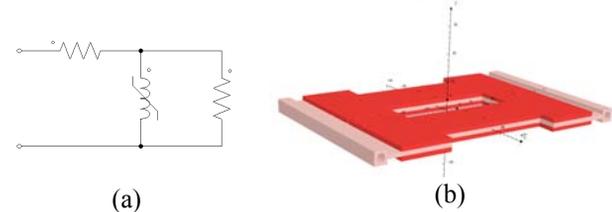


Figure 1: (a) Load model, (b) Elementary serpentine coil.

This results from the structure of the coils. Each of them consists of 25 layers of copper stacked together around the poles, among which 9 are cooled with thermal drain to a water piping. The elementary serpentine coil is represented in Fig. 1(b): It is made of two current carrier sheets with in between a thermal drain sheet (and Kapton to guarantee the insulation). Thus the equivalent model of the undulator is a transformer which secondaries are short-circuited. Seen from the primary, the model classically becomes the one shown in Fig. 1(a), where the resistance in parallel with the primary inductance is the secondary winding resistance reflected to the primary side. The calculations give a resistance value close to 140 m $\Omega$ , confirmed by the power tests.

The impact of this load behavior on the power supply design and on the achieved performances will be detailed hereafter. A solution will be proposed to improve the magnetic field settling time, which is strongly affected by the presence of this low value resistance.

## Topology of the Econverter

The structure of the 16 kW power converter is shown in Fig. 2. It is based on the following chain of elements: Dodecaphase rectifying unit + filter and energy storage + 2 interleaved PWM inverters + filter.

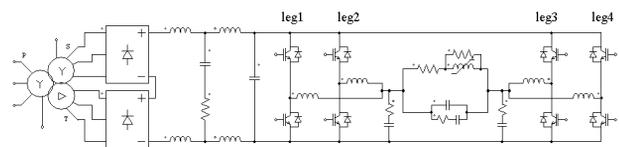


Figure 2: Power converter topology.

This topology choice is linked to the following considerations:

- AC-DC stage: Galvanic isolation between mains and output load is required. As the volume and weight of the power supply is not a major concern, an input stage

using a 50 Hz step-down transformer and a 12-pulse diode rectifier is preferred. This reliable solution enables us to reach reasonably good input current THD and power factor, with a DC link voltage predominating harmonic theoretically at 600 Hz (easy to filter). No additional power switches have to be controlled other than the ones used in the 4Q DC-DC stage. Thus the whole converter can be controlled using a single SLS digital control unit, as it will further be explained. This notably results in increased reliability and reduced costs.

- Intermediate DC stage: It is formed by a slightly damped LC filter used to attenuate the harmonics produced by the 12-pulse rectification and to mitigate the impact of AC mains perturbations. When the load acts as a generator, the energy is transferred to the capacitor bank (energy storage).
- 4Q DC-DC stage: The inverter section consists of two interleaved PWM H-bridges. A 180° phase shift is introduced between legs 1 and 2 (respectively legs 3 and 4) and a 90° phase shift between legs 1 and 3 (respectively legs 2 and 4). That way, the effective frequency at the output (and also in the DC-link HF filtering capacitors) reaches 4 times the IGBT switching frequency. This enables to conciliate the need of high bandwidth and good filtering of the output current. The inverter assembly includes film capacitors, used as decoupling capacitors and for the HF ripple filtering of the DC link voltage. With the cables coming from the capacitor bank, these capacitors form a LC filter which resonant frequency can be set close to the switching frequency (by using adequate cable length). The presence of this impedance only at the switching frequency guarantees equal current sharing in the output filter inductors without loss increasing.

*Power Eonverter Uzing*

The power converter has been dimensioned for the RL-type load model. The generation of the required current waveform then leads to a maximum ratio of 3 between the peak value of the output voltage (reached during the current transitions) and its steady-state value. The input transformer ratio has been determined on this basis.

""The LC filter at the rectifier output has a cut-off frequency of 25 Hz, which ensures good attenuation of the 12-pulse rectification harmonics with respect to the load current ripple.

""The IGBT switching frequency has been set to 17 kHz in order to trade-off between efficiency, dynamic response and reliability. The measured efficiency at nominal power of the converter is 85%. The IGBT modules (FF400R06KE3 from EUPEC) are water-cooled. The calculated junction temperatures are shown in Fig. 3. The power cycling capability of the IGBT modules can then be estimated using the power cycling curves provided by INFINEON for the 600 V IGBT3 standard modules: It is roughly  $7 \cdot 10^{10}$  cycles at 5 Hz operation and  $10^9$  cycles at less than 1 Hz operation. As regards the IGBT switching

dead time, it has been reduced to less than 1  $\mu$ s in order to limit the zero-crossing distortion of the output current.

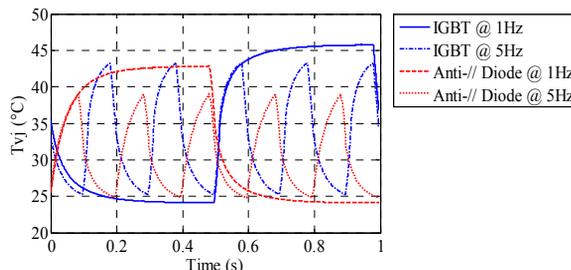


Figure 3: Power switch junction temperatures0

""To overcome the resolution limits of classic digital pulse width modulators, a special pulse repetition modulation (PRM) has been implemented by the Paul Scherrer Institute for the SLS digital controllers [2]. This PRM strategy generates low-frequency harmonics, which influence on the load current ripple has to be analysed. In our application, the PRM spectrum can contain sub-harmonics of the PWM carrier-frequency down to 450 Hz (1/37 of the PWM frequency) depending on the PWM duty cycle. With the RL-type load model, the output current distortion due to the low-frequency PRM harmonics does not exceed 10 ppm of the nominal current, in particular for the 450 Hz harmonic. The higher order harmonics are damped by the output filter, which has been designed with an attenuation of 40 dB at the switching frequency and 65 dB at 68 kHz (4 times the switching frequency).

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With the reel load, it is assumed that the magnetic field ripple will be smaller than with a RL-type load. In fact, a part of the current ripple will be bypassed to the thermal drain copper sheets being part of the undulator structure, which results in reduced field ripple.

""However, a serious issue lies in the magnetic field settling time: As it can be seen in Fig. 4, the current flowing through the load primary inductance (which is roughly the image of the magnetic field) has a very slow settling time (about 300 ms).

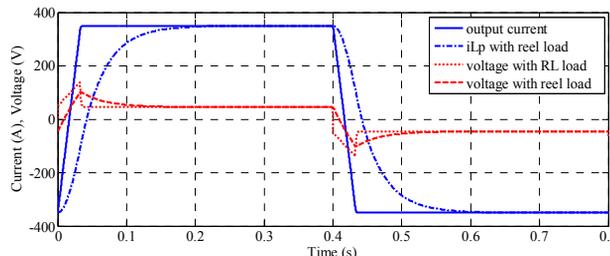


Figure 4: Output waveforms in AC mode of operation.

""To overcome this problem, the thermal drain sheets (TDS) are currently under modification to increase the resistance value of the load secondary circuit. The general idea is to insert gaps in the sheets as shown in Fig. 5. That way, the total magnetic flux which crosses each TDS window (then surrounding two adjacent poles instead of only one) is

zero. With a resistance increase by a factor of at least 10, the 100 ms target for the magnetic field settling time can be reached.

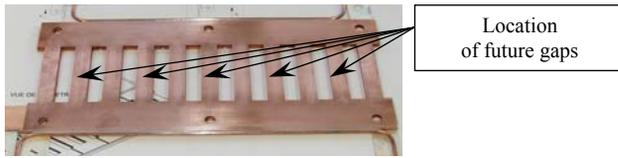


Figure 5: Modification of the thermal drain sheets

### Digital Control Loop Design

As mentioned previously, the whole converter can be controlled with a single SLS digital control unit. The performances of these digital control cards have been widely described in [3]. The designed control scheme is based on two nested loops: A PID controller is used for the inner voltage loop. For the outer current loop, a PI controller implemented under a R.S.T form is adopted. The parameters of both controllers have been derived from a pole placement such that the voltage and current closed-loops behave like second order systems. Furthermore, the voltage controller has been designed so as to compensate for the control delay which is roughly equal to the sampling period (half the PWM period).

Under RL load, the achieved control bandwidth for the current loop is 700 Hz, with a 13 dB gain margin and a 40° phase margin (for a load inductance at its minimum value). The polynomial T is a simple gain chosen to ensure unity gain to the current closed-loop. Thus, no undesirable zero is introduced in the closed-loop transfer function, which ensures no current overshoot.

With the reel load, the control loop parameters had to be optimized to achieve stable operation.

### Simulation and Experimental Results

Figures 6 and 7 present the simulations for both load models of a current transition from -350 A to +350 A, with a di/dt set to 20 kA/s. With the RL-type load model, the current settling time is less than 50 ms, the overshoot almost equal to zero, and the tracking error in the ramps around 3% (which corresponds to a phase shift between the load current and its reference of about 0.5 ms).

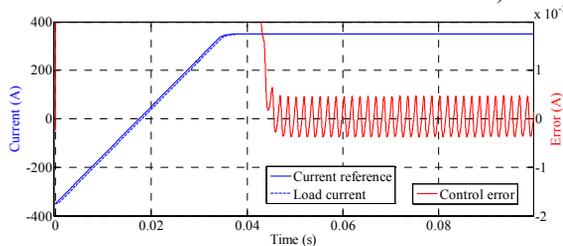


Figure 6: Simulation with the RL load model

With the reel load, the current settling time is close to 60 ms and the overshoot around 30 mA. The experimental results match the simulations, as can be seen in Figure 8 for the RL-type load. The next step will be to re-adjust the controller parameters when the undulator with the

modified TDS will be available. The performances should then approach those obtained under RL load.

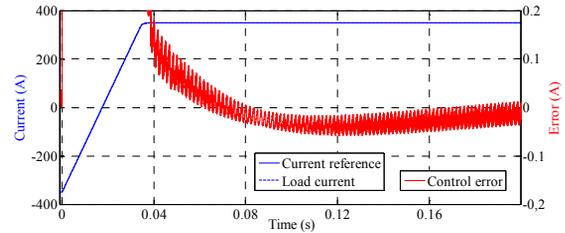


Figure 7: Simulation with the true load model

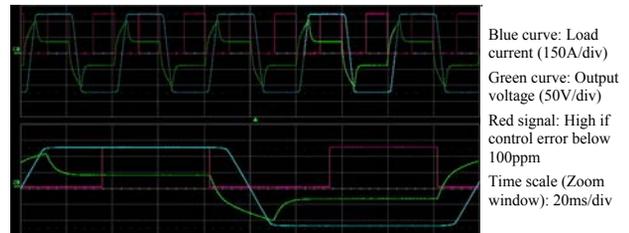


Figure 8: Operation at 5 Hz on a 110mΩ - 3mH test load

## CORRECTOR POWER SUPPLY DESIGN

A set of eight bipolar power supplies is needed to feed the correction coils split between the entrance and the exit of the undulator. These correctors are necessary to keep the field integral as low as possible during the main field transitions and to maintain the beam trajectory on the reference orbit. The structure of these power supplies, rated between 10 A / 100 W and 20 A / 200 W, is based on the use of either single or paralleled power operational amplifiers (PA12A from APEX). The current settling time consecutive to a polarity switching at the maximum current is around 15 ms (load time constant: 3 ms). The current precision is 100 ppm. In order to drive the corrector power supplies synchronously with the current in the main power supply (major requirement for a good correction), a special device has been developed: It consists of a 80 MHz microcontroller, on which the correction tables are shipped, and fast ADCs which generate at a 1 kHz rate the analog setpoint signals driving each of the nine power supplies. With this device, the 1 ms synchronisation requirement between the power supplies is met.

## CONCLUSION

The designed power supplies meet the dynamic response and current precision requirements. Moreover their structure is rather simple, which favours reliability and eases up maintenance.

## REFERENCES

- [1] F. Marteau, "Development of an Electromagnetic / Permanent Magnet Helical Undulator for Fast Polarisation Switching", PAC'09.
- [2] F. Jenni, M. Emmenegger, "A Fully Digital PWM for Highest Precision Power Supplies", EPE 2001.
- [3] L. Tanner, F. Jenni, "Digital Control for Highest Precision Accelerator Power Supplies", PAC'01.