



PAUL SCHERRER INSTITUT



SLS-PRE-TA-1998-0110

5. November, 1998

A 3 Hz, 1MW_{peak} Bending Magnet Power Supply for the Swiss Light Source (SLS)

**G. Irminger,
M. Horvat,
F. Jenni,
HU. Boksberger**

**PSI/AEI
Division Electrical and Electronics Engineering**

This paper was presented at the EP² in Grenoble 21./22.10.1998

A 3 Hz, 1MW_{peak} Bending Magnet Power Supply for the Swiss Light Source (SLS)

G. Irminger, M. Horvat, F. Jenni, HU. Boksberger
(all PSI/AEI Switzerland)

Introduction

The Swiss Light Source (SLS) is a dedicated high brightness synchrotron light source under construction at the Paul Scherrer Institute (PSI) in Villigen, Switzerland. The accelerator complex includes a 2.4 GeV electron storage ring of 288 m circumference, a full energy booster synchrotron (Booster) of 270 m circumference and a 100 MeV linear pre-injector (LINAC) [1].

The booster lattice is based on a FODO cell structure with all the combined function dipoles powered in series, 48 BD and 45 BF magnets. This design offers significant advantages, such as low power consumption, flexible repetition rates and field ramping [2].

To power the magnets in a booster synchrotron it is quite popular to use a resonant WHITE CIRCUIT, as described by M.G. White et al. (1956). This scheme is very useful for high repetition rates and circuits with high Q values [6,7].

In our case the White Circuit becomes less attractive, since the reactive energy stored in the magnets is low (approx. 28 kJ) with respect to the DC-power and furthermore, a repetition rate of 3Hz is sufficient to fill the storage ring in 2-3 minutes.

We have decided to use a switched mode power supply, offering the following features:

- flexible choice of the repetition rate up to several Hertz sinusoidal
- free programmable ramping profile for the current between a triangle and a $(1 - \cos\omega t)$ -function (the choice of low dB/dt at injection to reduce sextupole field induced by eddy current in vacuum chamber). In addition, a smooth variation of $u(t)$ reduces delay line mode effects
- possibility of a low duty cycle mode for top-up operation; unlimited dead time between pulses
- possibility to run the booster in a storage ring mode up to 1.7 GeV

Load and Magnet Parameters

All 93 combined function magnets are connected in series, representing a load of 0.6 Ω and 80 mH. The design specifications ask for a peak current of 950 A at a maximal ramping frequency of 3 Hz. This results in a current slew rate of 10 kA/s and a 1000 V peak voltage requirement. The magnets were optimised not to exceed the 1 kV voltage isolation level in order to avoid HV practice and requirements.

In order to minimise the heat loss to the tunnel the current density for the cabling was limited to 1 A/mm². The 700 m cable run will add an extra 22 m Ω resistance.

An average of 205 kW is required to power the dipole magnets. At 3 Hz sinusoidal operation, the power swing between + 750 kW and - 200 kW peak. Figure 1.1 and 1.2 show the power, current and voltage wave forms for triangular and sinusoidal ramping respectively.

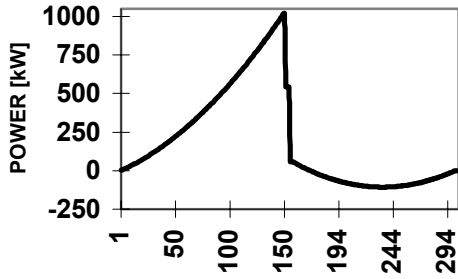


Figure 1.1: Triangular Ramping

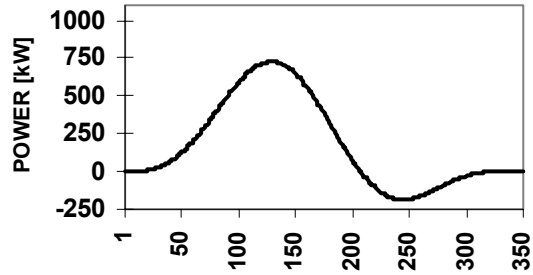
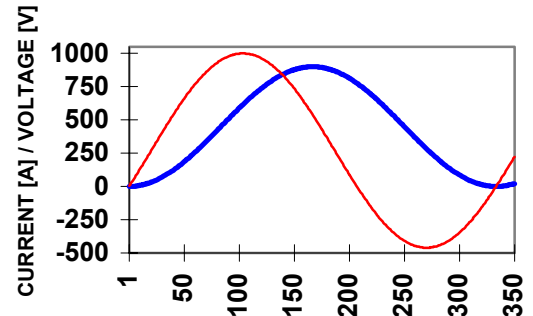
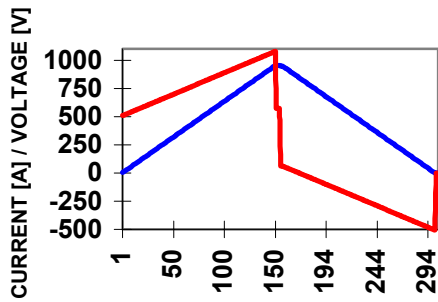


Figure 1.2: Sinusoidal Ramping



The following specifications for current/time performances were based on the tolerances of the booster's FODO-lattice [2]:

Long term stability	10 s - 8 h	40 ppm	of I_n
Mid term stability	100 ms - 10 s	20 ppm	of I_n
Short term stability	< 100 ms	10 ppm	of I_n
Reproducibility	per year	100 ppm	of I_n
Accuracy (absolute)	at injection (4% I_n)	1000 ppm	of 4 % I_n
	at nominal current I_n	1000 ppm	of I_n

Utility Parameters

The electrical utility supply for the SLS is fed from the PSI 50 kV substation with two primary feeds: one with 970 MVA and one with 413 MVA short circuit capacity.

A 10 MVA transformer steps down the voltage to 16 kV for the transport of the energy to the SLS Technical Building. The resulting short circuit capacity at the 16 kV level is at least 124 MVA.

A standard oil insulated 1.6 MVA utility step down transformer will feed the booster magnet power supply. It has a short circuit impedance of 6% resulting in an overall short circuit capacity of 21 MVA.

Considering above short circuit impedances, a 210 kW DC-load being switched directly to a single 1.6 MVA transformer would cause its voltage to sag by 1%, however still within the standard specifications of voltage. On a momentary basis, the maximal sag peaks 2.6% for a full load drawn directly from the mains.

Power Supply Design

System analysis using a resonant WHITE CIRCUIT, as described by M.G. White et al. (1956), showed very inconvenient results due to the low Q value in the circuit and the low repetition rate of 3 Hz.

Our investigations showed the feasibility of a snubber-less switched mode two quadrant power supply. If a DC/DC chopper is staged in series, ideally, a constant power flow from the line can be achieved reducing the voltage fluctuations for other loads. The block diagram is shown in Figure 2.

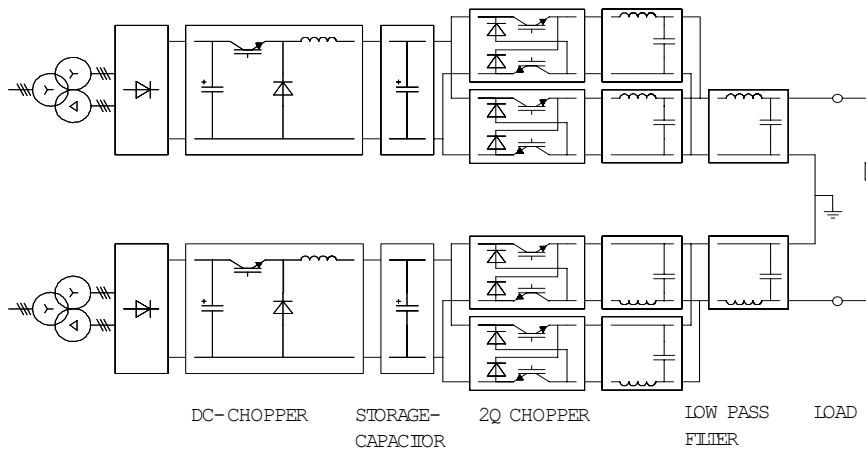


Figure 2: Power Supply Blockdiagram

Output Current

A small signal control loop bandwidth of 1 kHz is required for the power supply. With the new range of SIEMENS IGBT (BSM400GA120DL) and a very compact design, a switching frequency of 10 kHz becomes feasible. In order to operate within the practice of having the switching losses equal to the conduction losses we opted for paralleling two power units, each delivering half of the power supply's nominal peak current of 950 A. The estimates for the losses add up to 1.5 kW per IGBT at 300 A average current. Six paralleled IXYS DSEI 2X61-12b soft recovery diodes were selected as free wheeling diodes. They allowed to significantly reduce the commutation losses and the path impedance.

Output Voltage

To avoid HV-practice and restrictions, the voltage swing has to be limited to less than 1000 V. This can be achieved by either grounding the magnet circuit half way or by using two power supply units with a grounded midpoint. We chose the latter. It resulted in a total complement of four power units. Each power unit carries half the current, i.e. 475A and half the voltage, i.e. 500 V.

Output Filter

Operating the two switches of each power units phased by 180 deg doubles the effective frequency at the output to 20 kHz. The first filter stage is designed for an attenuation of 30 dB at 20 kHz. The Q was reduced to about unity in order to limit the voltage overshoot in case of a load shed to 30 %.

The two series modules (each consisting of two paralleled units) are phased by 90 deg in order to (ideally) cancel the 20 kHz. The second filter stage attenuates 43 dB at 40 kHz. The resulting voltage ripple should be well below 1 V.

Control / Regulation

Mains current and storage capacitor voltage (DC-DC-converter)

As mentioned before, the magnet current requirements lead to a pulsation of the capacitor voltage u_C and consequently also the mains current i_m ; however, the low frequency pulsations of the mains current should be avoided. Therefore, mains rectifier and storage capacitor were decoupled with a DC-DC-chopper (DC-DC-converter).

Both goals, a low pulsation of the mains current and a stable average value of the storage capacitor voltage, have to be fulfilled as good as possible with an appropriate control scheme. The 2Q-chopper as a load to the storage capacitor can be modelled with a differential resistor $r_d = -(u_C / i_m)$. Mains, rectifier and the controlled DC-chopper are replaced by a voltage source with the source resistance R_S as shown in Figure 3.

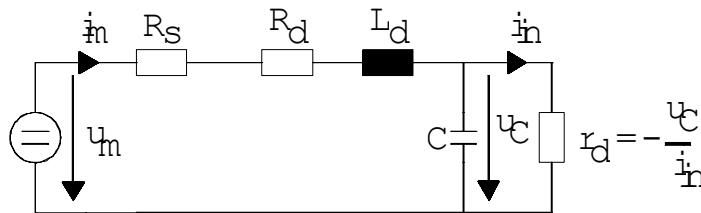


Figure 3: Stability Model for DC-Chopper

The analysis reveals that such a circuit itself can be unstable under certain load conditions. Stability requires, that $|(R_S + R_d) \cdot r_d| < |L_d / C|$ and $|r_d| > |(R_S + R_d)|$ must be true. For the majority of the applications, the storage capacitor gets coupled directly to the voltage source, ensuring circuit stability; in our case up to about 6kA at 500V capacitor voltage. This would be more than sufficient for our application.

The task of stabilising the amplitude of the mains current can be modelled by varying the resistor R_S . A constant mains current would imply an infinite value for R_S . However, it is not possible to stabilise the circuit for higher values of R_S .

A sophisticated controller was developed which stabilises the average value of the capacitor voltage and limits the pulsation of the mains current to less than 20% of its average value. Figure 4 shows the predicted current and voltage values versus the time for a sinusoidal load current of 950A with 3Hz.

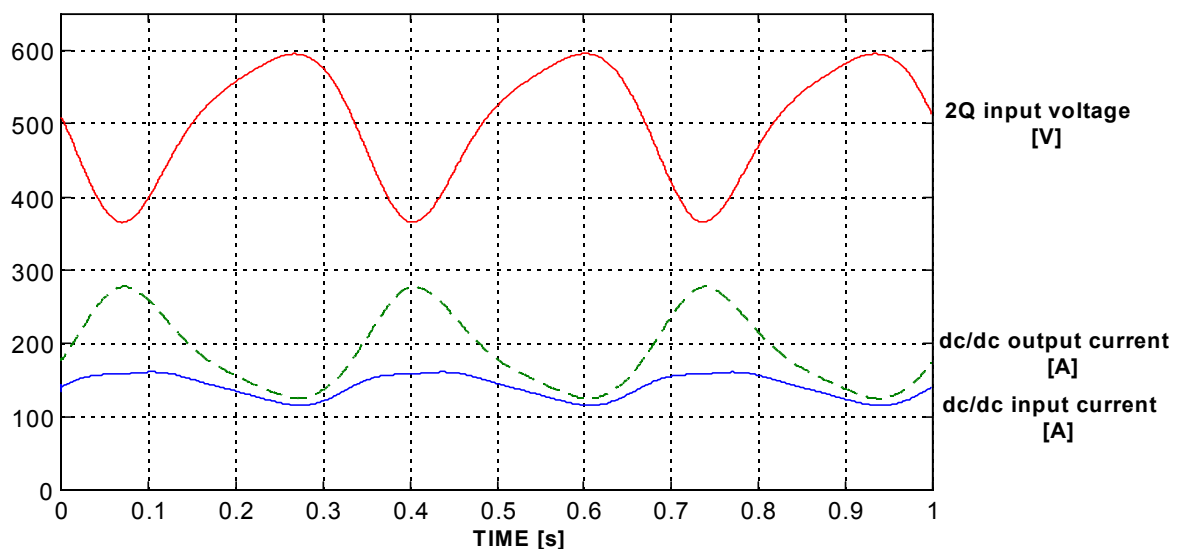


Figure 4: DC-Chopper Currents and Output Voltage

The dynamic operating parameters are visualised in Figure 5 as a voltage-current-diagram showing the variations at the input of the 2Q-converter versus voltage and current at the input and output of the DC-DC-chopper superimposed to the stability criteria. It can be seen, that the circuit operates partly in unstable regions (2Q-Input). The good suppression of the pulsation of the DC-chopper input current and therefore of the mains current is well noticeable.

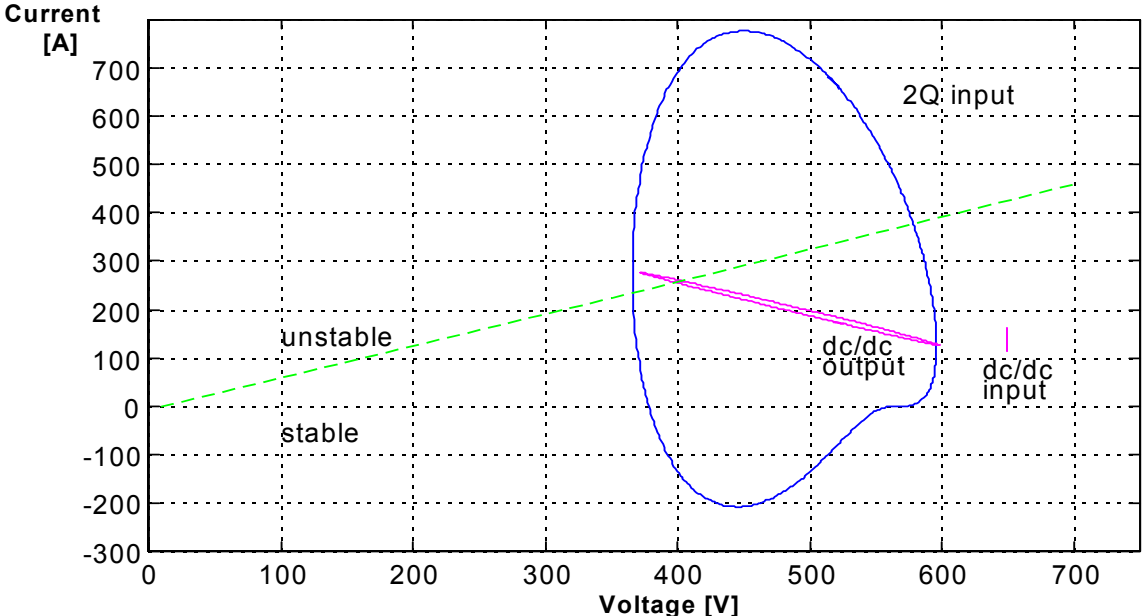


Figure 5: Voltage/Current Diagram of 2Q-Converter and DC-DC-Chopper

Figure 6 shows the same properties for twice the storage capacitor value. The average voltage could be raised from 500V to 550V yet keeping the same peak voltage. The voltage pulsations would be reduced by more than factor two.

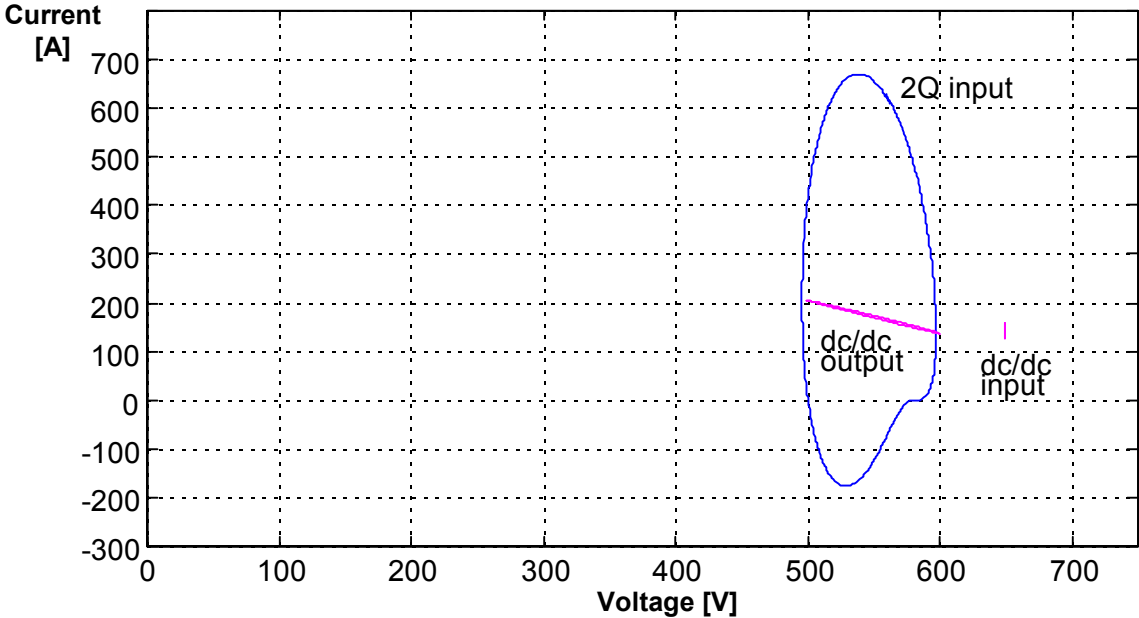


Figure 6: Voltage/Current Diagram of 2Q-Converter and DC-DC-Chopper with Twice the Storage Capacitor Value

Load Current Regulation (2Q-Chopper)

Care had to be taken to ensure proper current and voltage sharing between the power modules. Each power unit has its own local current regulator to assure equal current loading. The two units forming a power module are controlled for symmetrical voltage sharing by an extra loop. An overall current control loop ensures the power supply's performance required by the magnet.

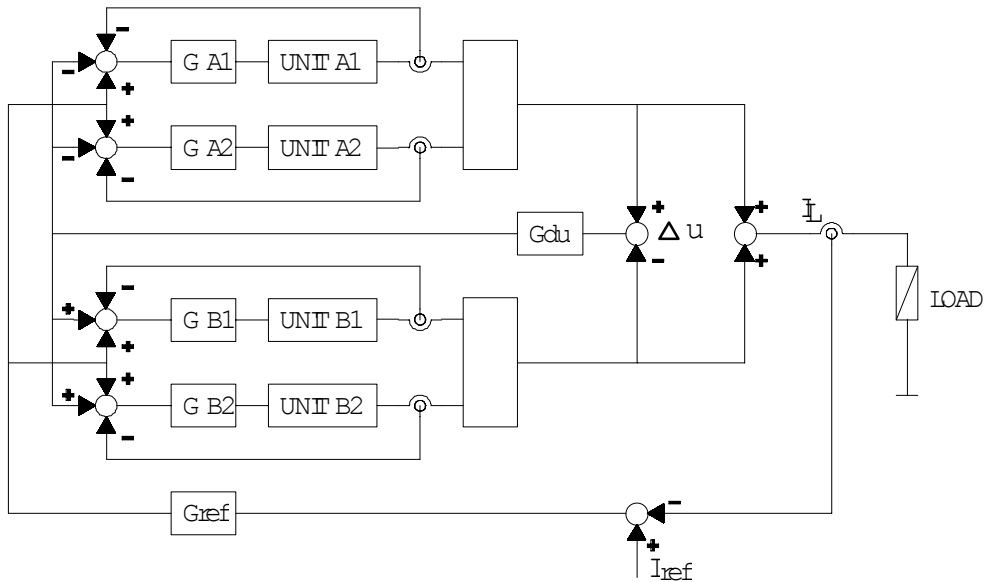


Figure 7: Control Blockdiagram of the 2Q-Chopper

Measurements

Up to now (10.08.1998), one power unit has been built and is currently under test. The measurements performed showed a good coincidence with the design values simulated by PSPICE.

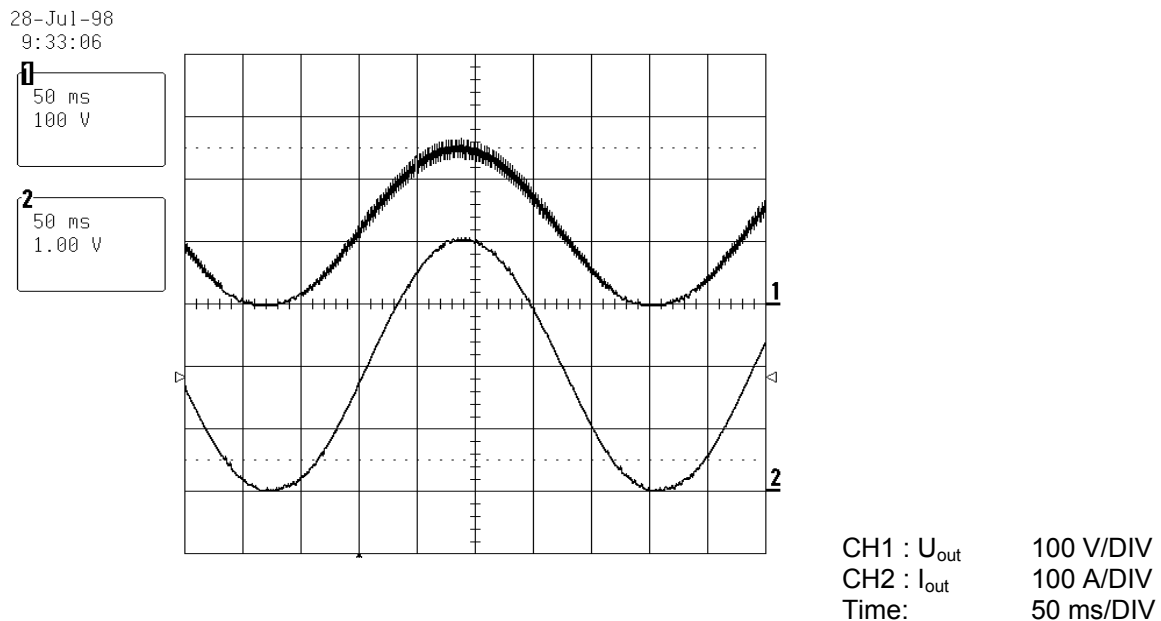


Figure 8: Measurement of a Single Power Unit ($R_L = 0.6 \text{ Ohm}$, $L_L = 2.5 \text{ mHy}$)

Conclusion

The substitution of the classical White Circuit by a switched mode power supply for the Swiss Light Source opens a new range of flexibility just limited by the peak voltage and peak current design values. The high switching frequency per device results in small reactive filter components and a high control bandwidth.

The ideal of a constant current flow from the mains could not be achieved. Stability governs the lower limit of the fluctuation.

Acknowledgements

The authors would like to acknowledge the support of the SLS team, especially W.Joho, to embark on this new design.

References

[1]

Streun-A, et al, Paul Scherrer Institute, CH5232 Villigen, Switzerland; **THE SLS ACCELERATOR COMPLEX, AN OVERVIEW**, EPAC98

[2]

Gough-C, Irminger-G, Joho-W, Marchand-P, Munoz-M, Schlott-V, Schulz-L, Streun-A, Vrankovic-V, Wiegand-P, Zichy-J, Paul Scherrer Institute, CH5232 Villigen, Switzerland; **THE SLS BOOSTER SYNCHROTRON**; EPAC98

[3]

Marks-N; Poole-DE; **The choice of power converter systems for a 3 GeV booster synchrotron**; EPAC96. Fifth European Particle Accelerator Conference. Institute of Physics Publishing, Bristol, UK; 1997; 3 vol. xxxix+2704 pp. p.2331-3 vol.3

[4]

Zhang-FQ; **Simulation of power supply for rapid cycling accelerator**; Proceedings of the 10th Symposium on Accelerator Science and Technology (JAERI-Conf 95-021). JAERI, Ibaraki-ken, Japan; 1995; xx+468 pp. p.115-17

[5]

Bothe-W; Pillat-P; **Magnet excitation circuits for DESY II** ; IEEE-Transactions-on-Nuclear-Science. vol.NS-32, no.5, pt.2; Oct. 1985; p.3752-854

[6]

van-Lieshout-L; **PWM inverter for White resonant circuit** ; EPE '91. 4th European Conference on Power Electronics and Applications. Litografia GEDA, Torino, Italy; 1991; 4 vol. (657+665+725+737) pp. p.221-4 vol.4

[7]

Hettel-R; Averill-R; Baltay-M; Brennan-S; Harris-C; Horton-M; Jach-C; Sebek-J; Voss-J; **The 10 Hz resonant magnet power supply for the SSRL 3 GeV injector**; Conference Record of the IEEE Particle Accelerator Conference. Accelerator Science and Technology (Cat. No.91CH3038-7). IEEE, New York, NY, USA; 1991; 5 vol. 3283 pp. p.926-8 vol.2

[8]

Lieshout-L.A.E.; **800 kW Four Quadrant Amplifier with large full signal bandwidth for fusion experiments consisting of IGBT's and aktive filter**, EP2 Forum 95, Electrical Power Technology in European Physics Research, CERN Volume ETG 43e, vol. 2-801..806

[9]

Lieshout-L.A.E, Colijn-A.J.J.; **900 kW Two-Quadrant switched mode power supply with large bandwidth and extremely low ripple for synchrotron particle acceleration consisting of IGBT" and passive filter**, EPE97 European Conference on Power Electronics and Applications, Trondheim, Volume 2, p 268.