500A/150V DC SWITCHED MODE POWER SUPPLY FOR MAGNETS

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***Abstract* - This paper presents the specifications, the design and experimental results of a 500A/150V DC current source power supply, which will be used for tests with bending magnets at the LNLS. The chosen topology is a set of 12 parallel switched modules using Buck topology, supplied by a three-phase bridge rectifier with an LC filter.**

***Keywords* – power supply, Buck converter.**

I. INTRODUCTION

The Brazilian Synchrotron Light Laboratory - LNLS has constructed and operated the only Synchrotron Light source in the southern hemisphere [1]. This source has been open to users since 1997.

Currently, the energy of the stored electron beam in the storage ring is 1.37GeV. There are studies to increase this energy to 1.6GeV, which will imply an increase of the bending magnet field to about 2T. The bending magnets are responsible for the closed orbit of the electrons. To reach this field, the current of these magnets must be increased from 300A to 500A, which implies building of a new power supply.

Today, the DC current source used to supply the 12 bending magnets associated in series is a 300A/900V switched mode supply. The topology of this source consists of a 12 pulse controlled rectifier with an LC damped filter (90% of the total output voltage) in series with a parallel association of 10 switched modules (which is responsible for 10% of the total output voltage) [2]. While the switched modules compensate fast variations in the output current, the controlled rectifier compensate the slow variations. The main advantage of this configuration is the low current and voltage that are switched, which reduces the EMI.

To verify the behavior of the bending magnets in the new situation, we have designed and built a DC current source power supply of 500A/150V, enough to do the tests with a single bending magnet, which must have in this operation condition resistance of 0.25Ω and inductance of 84mH. Some topologies were analyzed [3-6], but the topology chosen for this power supply uses 12 switched modules operating in parallel, supplied by a three-phase bridge rectifier with LC filter, due to simplicity and reliability. Moreover, if the tests with one bending magnet show satisfactory results, this power supply will be used in the construction of a 500A/1600V power supply to the series association of the 12 bending magnets, using the same topology of the present current source, which will decrease the final cost.

II. CIRCUIT DESCRIPTION

Figure 1 shows the block diagram of the power supply circuit. Each one of those are briefly described below.

A. Command and Protection.

The command and protection circuit is connected to the 220V Y secondary of the standard three-phase transformer. The power of the transformer must not be less than 100kVA.

The protection is made by ultra-fast fuses and over-current thermal relays. A three-phase voltage monitor detects under and over-voltages in the transformer secondary, acting in the main contactor. A transient filter in the "Bucket" configuration protects the rectifier bridge input against surges [7]. Others auxiliary electronic circuits supervise voltages, currents and temperatures at many points of the power supply, also acting in the main contactor if any failure happens.

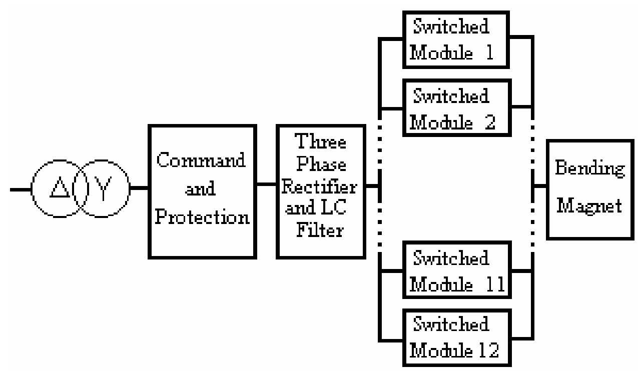

Fig. 1. Block diagram of power circuit.

The main contactor, besides power on and off the power circuit, connects a discharge resistor to the filter when the source is off. An auxiliary contactor connects to the start resistors in series with the rectifier, to limit the capacitors inrush current.

B. Three-phase rectifier and filter.

The DC voltage that supplies the switched modules is obtained by a three-phase rectifier bridge with a LC filter in its output, as shown in figure 2.

The inductance and the capacitance were calculated with the techniques described in [8], and results in the values of 100µH e 9.6mF, respectively. This capacitance was obtained using a 800µF capacitor in each switched module. Figure 3 shows the simulation results to this circuit using PSPICE, with the calculated values of the voltage and current in one of the input phases (V_{phase}=220V and R=1Ω) and the output voltage, before and after the LC filter.

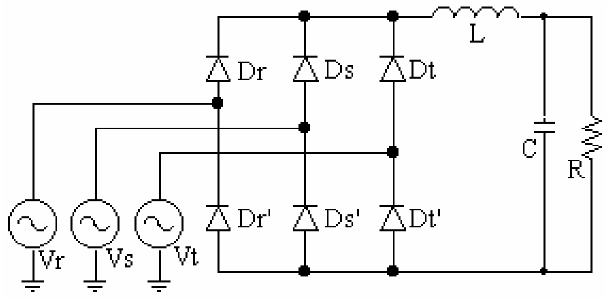

Fig. 2. Three-phase Rectifier Bridge with LC filter.

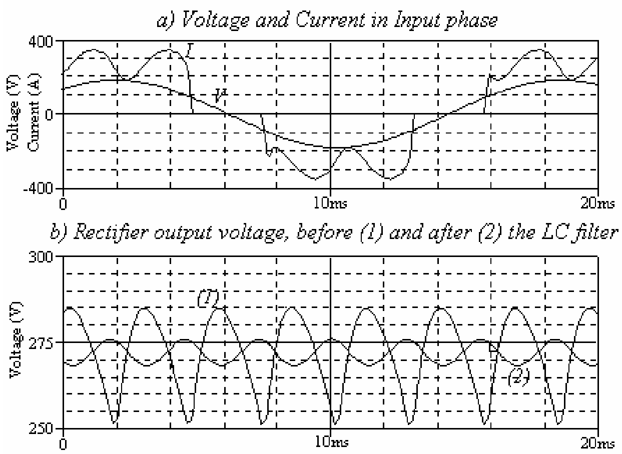

Fig. 3. Waveforms to Figure 2 circuit.

C. Switched Modules.

The switched modules are basically Buck converters, without the output capacitor. Figure 4 shows the simplified circuit of one switched module. The main advantage of the use of 12 parallel-switched modules is that each module conducts only a small fraction of the total output current. Moreover, in order to decrease the di/dt and dv/dt, the modules are turned on and off with intervals of 1µs approximately.

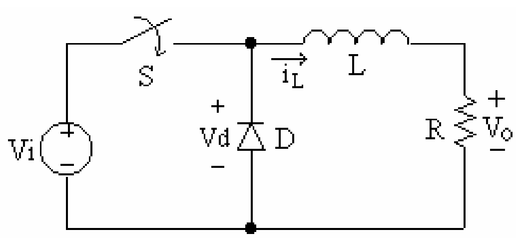

Fig. 4. Simplified circuit of one switched module.

The switch used is an IGBT (Insulated Gate Bipolar Transistor) in a commercial module, which has internally the diode. The output inductance value chosen (300µH) is sufficiently smaller than the inductance of bending magnet so the voltage drop across its can be neglected.

Figure 5 shows the simulation results using PSPICE, for four switched modules, with the input voltage 40V and a 10Ω resistance series with a 10mH inductance as load. The switching frequency is 50kHz and the switched module inductances are 100µH.

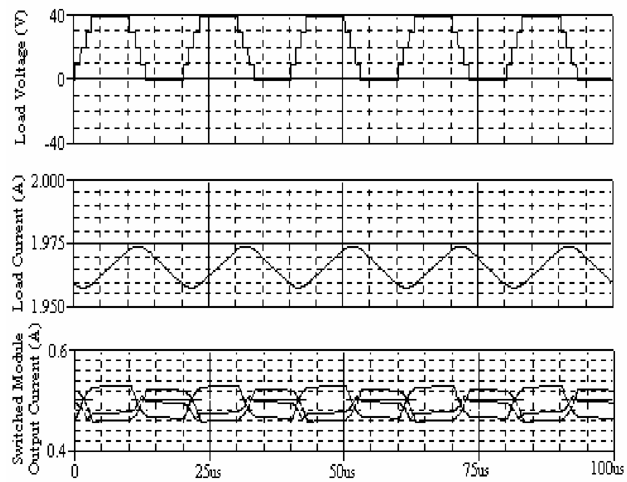

Fig. 5. Waveforms to 4 parallel switched modules.

III. CONTROL CIRCUIT

The output current control is made by the pulse width of the switch command signal of the switched modules. Current Limit Modulation (hysteresis control) is used in order to ensure that the output current ripple stays within the predefined limits.

The output current is measured with a DCCT (DC current transformer) and compared with the reference voltage. The amplified difference is fed into the hysteresis comparator which sets the trigger sequence logic circuit. This circuit, across a commercial Semikron isolated drive, turns on and off the IGBT of the switched modules.

IV. EXPERIMENTAL RESULTS

After the construction of the power supply, several tests and measurements were performed, for many output current values. Here we show only the results for 500A output current.

Figure 6 shows the input current, voltage and power in one of the phases of the power part. These waveforms are very similar to those shown in Figure 3a. The rms value of the input current is 169A for a 119V input phase voltage, which gives a total input voltampere of 60.3kVA. The total input power was 56.4kW, which gives a power factor to the power part of 0.935. This value is very near the calculated power factor (0.94).

Figure 7 shows the rectifier output voltage, before and after the LC filter. The average rectified voltage was 275V. The peak-to-peak ripple was attenuated by the filter from 30V to 15V approximately.

Figure 8 shows the DC output current and voltage. The average output voltage was 110V, which gives an output power of 55kW. The losses in the control circuits and fan were 250W, which added to the input power gives a 97.1% of efficiency. The losses in the input transformer are not computed in this value.

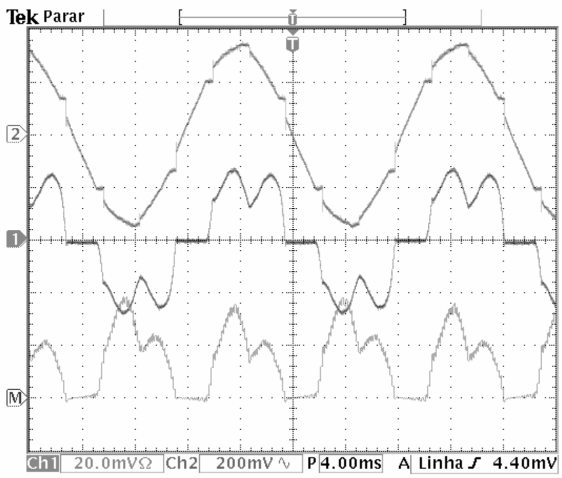

Fig. 6. Input waveforms to the power source: a) Ch2: Voltage (upper trace: 100V/div); b) Ch1: Current (middle trace: 200A/div); c) Math: Power (lower trace: 100kW/div)

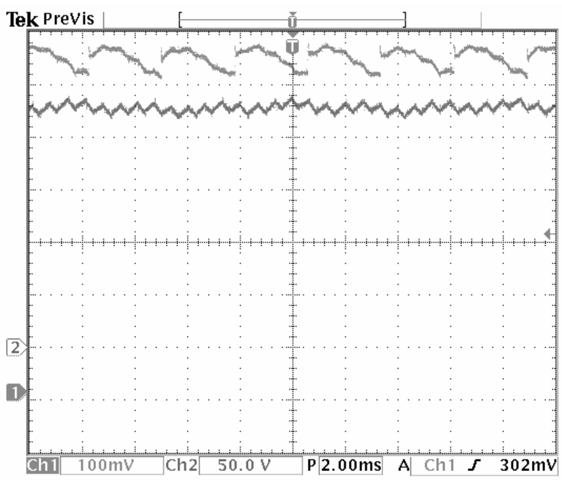

Fig. 7. Rectified voltage, before (Ch2, upper trace: 50V/div) and after (Ch1, lower trace: 50V/div) the LC filter

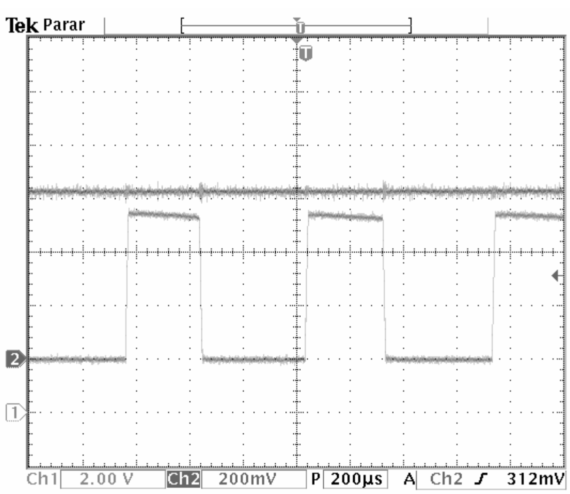

Fig. 8. Output Current (Ch1, upper trace: 120A/div) and Voltage (Ch2, lower trace: 100V/div).

The switching frequency was approximately 1.5kHz. The measured resistance of the bending magnet with the cable is 0.22Ω, 12% lower than the calculated value.

Figure 9 shows the output current ripple, approximately 0.6App (0.1%). This ripple is given by the adjusted hysteresis limits of the control circuit, and is related to the switching frequency.

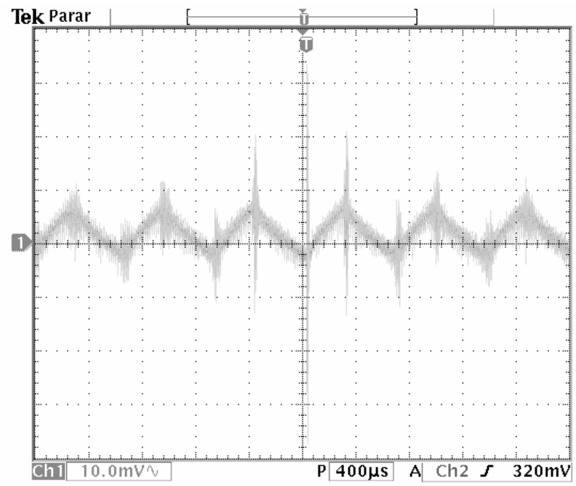

Fig. 9. Output current ripple (600mA/div).

Figures 10 and 11 show the output voltage details, where the sequential switched modules turn-on and turn-off can be seen.

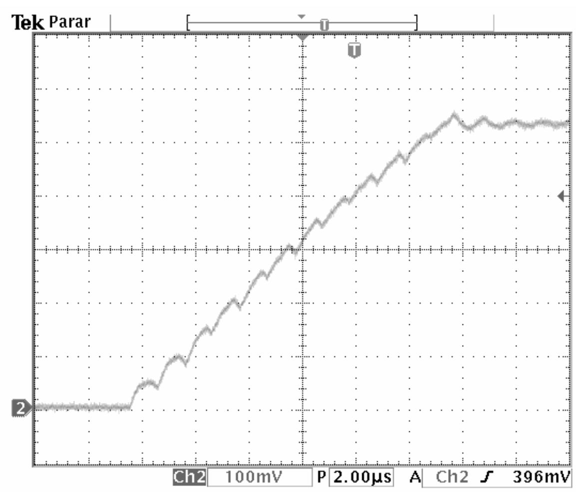

Fig. 10. Output voltage turn-on detail (50V/div).

Figure 12 shows the inductor current in one of the switched modules.

V. CONCLUSION

The tests performed in the constructed power supply have shown very good results, achieving the expected goals.

The efficiency obtained was excellent and the power factor is relatively high, very close to the calculated value.

Although the electromagnetic interference (EMI) was not measured, no effects on others equipments were observed.

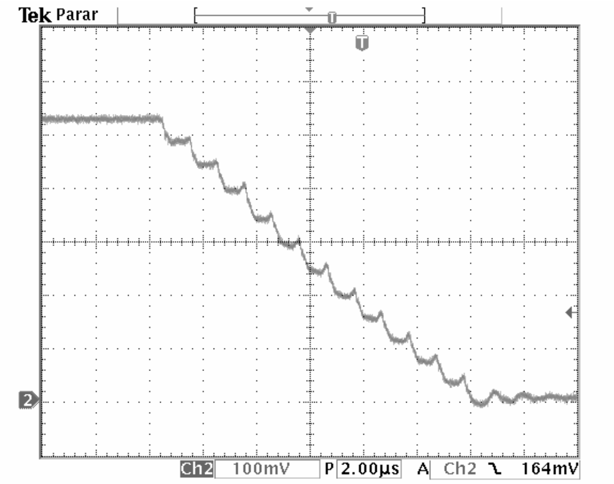

Fig. 11. Output voltage turn-off detail (50V/div).

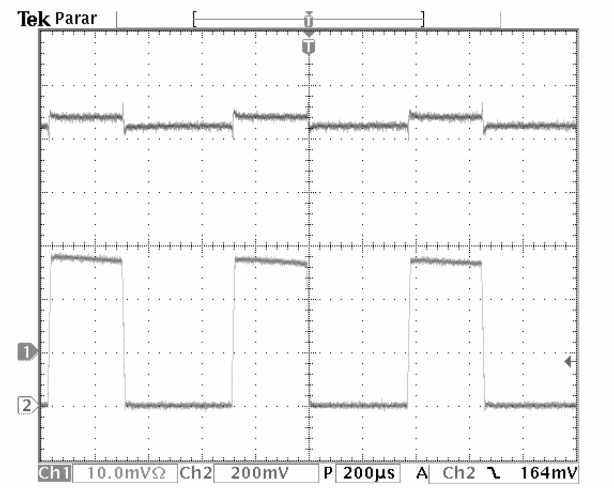

Fig. 12. Switched Module inductor Current (Ch1, upper trace: 10A/div) and output voltage (lower trace: 100V/div)

The output current ripple adjusted is sufficiently low to allow tests with the bending magnets and do not affect the power supply stability.

Although the power supply was designed for 500A output current, it is possible to work several minutes with 600A output current. After this time the power supply will turn-off by over temperature in the switched modules. If forced ventilation of the switched modules is implemented, it is possible for the power supply to work continuously at this current value.

The power supply was also tested with only switched modules, simulating a failure situation, and no problems were observed.

Now the power supply is being used to do measurements with the bending magnet, and if the tests are satisfactory, it will be used in the 500A/1600V power supply construction for the 12 bending magnets of the storage ring.

ACKNOWLEDGEMENT

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