

HIGH-SPEED HIGH-PRECISION PROGRAMMABLE MAGNET POWER SUPPLY
FOR A WIDE RANGE OF MAGNET TIME CONSTANTS

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Summary

Rapid current control in highly inductive loads requires a regenerative convertor whose output voltage is a multiple of that determined by the ohmic resistance. During the flat top of the pulse the convertor is phased back resulting in a relatively large ripple and a high reactive power. Controlled freewheeling using thyristors between the d.c. terminals and the neutral of the transformer winding improves the output waveform and reduces the power drawn from the mains without reduction of the dynamic performance. Twelve-pulse rectification, a passive smoothing filter with low stored energy and an active filter ensure an extremely low ripple and a fast dynamic performance.

Circuits and design principles are illustrated by describing a 220 V/6500 A pulsed power source for testing magnets. Control range 0-6500 A, max. di/dt 20 kA/s, stability 100 mA, p-t-p ripple 30 mA; magnet time constant between 0.05 s and 10 s. The current source is provided with a high-precision digital current programmer; current shaping is achieved with 8 adjustable parameters.

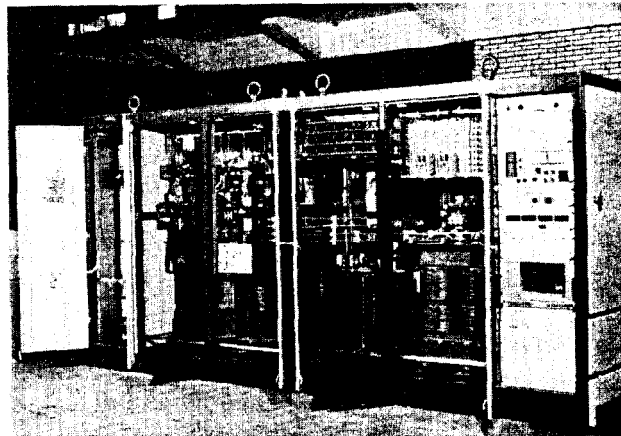
Introduction

In particle accelerator systems fast pulsed power supplies are used whose output current must follow accurately a pattern which is imposed by a computer. To obtain a rapid current variation in the inductive load, a maximum output voltage is required whose value is a multiple of that determined by the ohmic resistance. For reasons of efficiency and speed, these power supplies are preferably 6, 12 or 24-pulse regenerative convertors which can rapidly transfer the power from the mains to the magnet load or back into the mains.

During the flat top of the pulse the convertor is phased back resulting in a relatively large ripple and high reactive power. Controlled freewheeling reduces the above phenomenon. To bring the ripple down further, a smoothing filter is necessary comprising normally a damped LC arrangement. The amount of stored energy in this filter determines the degree of attenuation. As this is limited by the specified rapid current control, further smoothing is necessary with the aid of an active filter. This active filter comprises a power amplifier whose output is injected into the main circuit with the aid of an inductance in series with the load. It is clear from the above that the conflicting requirements - high-speed control and large attenuation of the ripple - demand an optimization of the combined passive and active filter arrangement. The design philosophy is best understood in the context of an example. For this a 220 V/6500 A power supply designed for testing magnets at CERN provides a suitable illustration.

Main circuit (fig. 1)

Two three-phase bridges are paralleled via an inter-phase transformer. A phase shift of 30 degrees between the two three-phase systems ensures 12-pulse operation.



Controlled freewheeling operation is obtained by thyristors between the d.c. terminals of each bridge and the corresponding neutral of the transformer winding. No fuses are used as the prospective short-circuit current flowing during the clearance time will not result in explosion of the thyristors. In case of an external short-circuit the fault current can be cleared by immediate control into inversion without damage to the thyristors. Smoothing is achieved by a passive and an active filter. The load current is measured by a zero-flux current transformer. Transformer, semi-conductors and chokes are water-cooled.

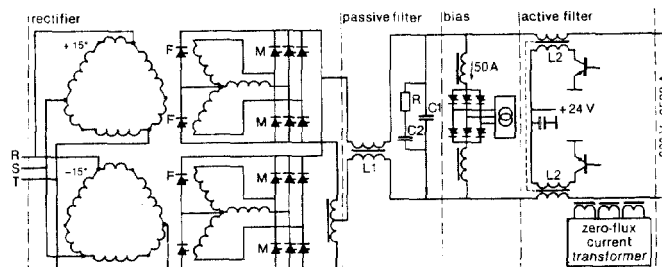


Fig. 1

To ensure proper closed-loop operation around zero-load current and to guarantee the required dv/dt at constant load current, a bias current of 50 A is generated by an auxiliary power supply. Proper control of the auxiliary thyristor bridge ensures reduction of the bias current to zero at load currents above 50 A.

Main parameters:	
. primary voltage	380 V, 3-phase, 50 Hz
. nom. secondary voltage	+ 220 V
. peak load current	6500 A
. r.m.s. load current	3000 A
. control range	0 - 6500 A
. max. di/dt	+ 20 kA/s
. max. dv/dt	+ 12 kV/s
. time constant range of magnet	0.05 - 10 s
. ripple current p-t-p	30 mA
. stability	100 mA

Control loop and block diagram (fig. 2)

The power supply is current-stabilized for frequencies up to 30 Hz. Below this frequency the admittance of the load (3), the load-adaptation circuit (6) and the current-loop integrator (5) form an ideal integrator with unity gain at 30 Hz. Above 30 Hz these blocks are by-passed by the voltage feedback which suppresses the output ripple and eliminates voltage excursions due to mains-voltage steps. Wide-band amplification is provided by the main loop (4) which drives the active filter and the thyristor firing circuit in parallel. According to their relative gains, voltage control is realized by the thyristor bridge, up to 180 Hz, by the active filter, onwards up to 20 kHz.

Any ripple originating from (1) is suppressed by the closed loop of (2) and (4) having a high internal gain. This loop has a stable unity gain at 20 kHz. Should the active filter saturate (voltage or current limiting) then the loop bandwidth drops to approx. 180 Hz with an unstable transfer characteristic.

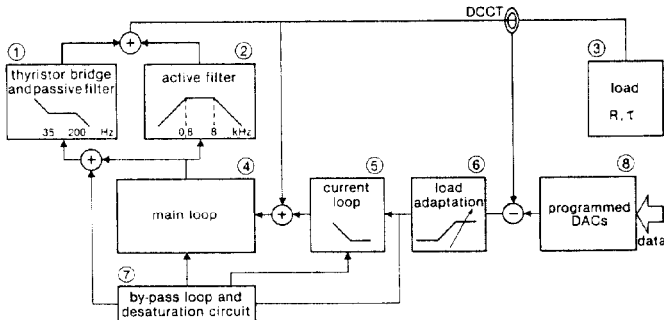


Fig. 2

Consequently the blocks (2), (4) and (5) will saturate. This phenomenon can be eliminated by using a by-pass loop (7) that takes over from the saturated blocks within 1 ms, thereby desaturating the active filter as well as the slow integrators (4) and (5).

When the reference voltage pulse becomes flat, blocks (2), (4) and (5) take over from (7) within 5 ms. The above combination may be considered as a highly linear power amplifier having a small signal bandwidth of 20 kHz.

Controlled freewheeling (fig. 3 and 4)

For a high output voltage (during build-up of the magnet current) only the main thyristors are fired resulting in rectification of the line-to-line voltage. For a low voltage, e.g. during the flat top, the line-to-neutral voltage is rectified by firing a main (M) and a freewheeling (F) thyristor. Voltage control is possible, in the same way as with a normal bridge, by variation of the firing angle. The above mode of operation reduces the line current and, hence, the out-of-phase power drawn from the mains. In fig. 4a the r.m.s. line current is plotted versus the output voltage at constant load current, assuming no current ripple and no overlap are present. The dotted line shows the r.m.s. line current, without operation of the freewheeling thyristors. The full line shows the same current when free-wheeling

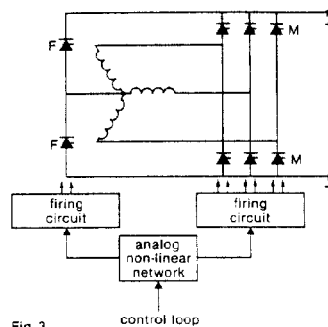


Fig. 3

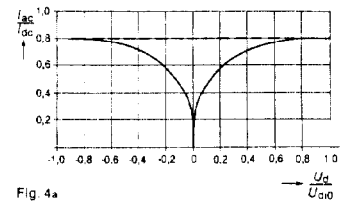


Fig. 4a

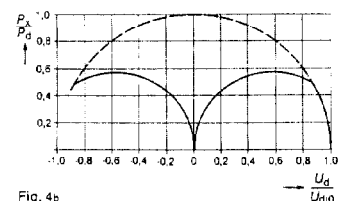


Fig. 4b

thyristors are operational. The corresponding reactive power is indicated in fig. 4b. To obtain smooth control from full inversion to full rectification, an integral firing circuit has been developed having the following features:

- nearly linear operation from full inversion to full rectification (gain variation less than 1:2)
- 12-pulse operation using a phase-locked loop circuitry which ensures equally spaced pulse patterns and, hence, no subharmonic components
- non-linear network programmable for
 - minimum ripple or
 - minimum reactive power or
 - maximum flat gain
- wide bandwidth: d.c. to 200-Hz a.c.
- short power pulses (100 μ s) enabling application of economic pulse transformers
- accurate current balance between two 30 degrees phase-shifted paralleled bridges.

Design of smoothing filter

The smoothing filter comprises a passive (LC) part, which reduces the peak-to-peak ripple to approx. 5% of the nominal output voltage, and an active part for further reduction. L_1C_1 is tuned to 120 Hz with C_1 as low as possible to obtain the required $-dV/dt$ with a negative 50-A bias current. Critical damping of L_1C_1 is obtained with RC_2 . The active filter provides for

- ripple reduction by a factor of 20
- production of sharp edges on the voltage waveform
- reduction of the voltage excursions.

The push-pull power amplifier is essentially a current source injecting into the choke L_2 . The injected current is converted to a voltage which is superimposed on the rectifier output voltage. This has the following advantages:

- wide bandwidth as the gain rises with frequency
- load-induced phenomena within the control range of the amplifier do not interfere with its operation
- zero mean output power since the magnet current contains no ripple.

The size of the active filter is mainly determined by the additional voltage that must be injected to obtain the required dV/dt during the rise and fall of the magnet current, and by the peak-to-peak ripple voltage that must be cancelled. A low cut-off frequency of the passive filter results in a low p-t-p ripple voltage (a) but also leads to a high

p-t-p voltage (b) to be injected by the active filter during rise and fall of the magnet current.

It is found that a good trade-off is obtained at $a/b = 0.5$.

The size of L_2 is determined by a trade-off between the rating of the power amplifier and that of the choke L_2 , since the power amplifier has to supply the magnetizing current only in order to induce the required voltage.

The larger the value of L_2 chosen, the smaller will be the power amplifier. An economic design is found by choosing L_2 to have the same value as L_1 for a typical class of large magnet power supplies. By using an auxiliary winding, optimum matching can be obtained. Diodes across the transistors prevent generation of overvoltages during a short-circuit in the main circuit. When this situation occurs, energy is transferred from the main circuit into the d.c. supply of the transistors. A large capacitor bank is used to store this additional energy without an excessive voltage rise. This storage capacity is also needed to supply the required peak power during voltage rise. The application of the injection choke L_2 considerably reduces the size of the transistor bank. Only 160 transistors are needed, with a total mean dissipation of 600 W, to obtain the required performance at 1.4-MW peak power.

Current measurement (fig. 5)

The control loop requires a current measuring device with an ability to reproduce up to 10-ppm accuracy, suitable for bi-polar operation with a large bandwidth, and with good transient response and low noise. A zero-flux current transformer is used comprising a magnetic integrator and a second-harmonic modulator. The current-carrying conductor is surrounded by three ring cores. A sensing winding W_3 on core T_1 provides the flux-rate feedback to a power amplifier which drives the ampere-turn compensating current through a common compensating winding W_2 .

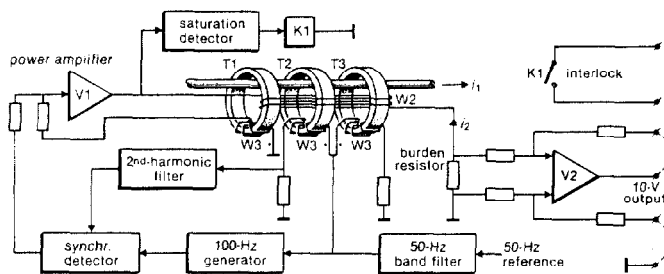


Fig. 5

The cores T_2 and T_3 serve as a second-harmonic modulator to establish zero-flux operation and thus ensure a perfect temperature-independent current balance. A specially developed load resistor, having a temperature coefficient of 0.1 ppm/K, converts the compensating current into a voltage signal which is amplified to give 10-V output at 6500 A. The correct operation of the zero-flux current transformer is monitored by a saturation detector. Faulty operation mostly results in saturation of the cores. The saturation detector is designed to generate a fast tripping signal.

Digital current programmer (fig. 6 and 7)

A waveform with linear and flat segments should be programmable according to the following requirements.

- . number of slopes 4
- . adjustment range of slopes ± 0.2 to ± 20 kA/s
- . resolution of slope adjustment 200 A/s
- . number of flat segments 4
- . adjustment range 0 - 6500 A
- . resolution 1 A
- . absolute accuracy ± 0.65 A
- . 1-day stability ± 0.13 A
- . adjustment range of duration of flat segments 0.01 - 10 s
- . resolution of duration adjustment 0.01 s

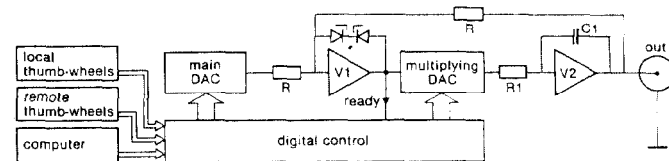


Fig. 6

As slopes should not have any discontinuity, combined digital and analogue circuitry is used, comprising a multiplying DAC followed by an integrator, as a programmable rate limiter.

The flat segments are generated by a high-accuracy 16-bits DAC. Each 'vector', comprising a flat segment and a slope, requires three characteristic parameters, viz:

- . flat-segment value I (A)
- . duration of flat segment t (s)
- . rate of change of current di/dt (A/s)

These can be adjusted either by local or remotely located thumbwheels or by a computer.

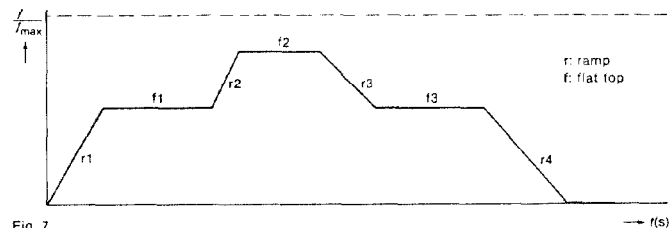


Fig. 7

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