Different power supplies for different machines

H.-J. Eckoldt
DESY, Hamburg, Germany

Abstract

Each time a new accelerator is built, the question of the right choice of technology for the power supplies (PS) is raised again. No specific advice can be given since the demands on the units as well as the available budget have a strong influence on the decision. An overview of the different technologies in the different machines is given here. On account of the large number of different applications, not every solution can be mentioned here but examples of different power supplies are shown. The categories are fast cycling machines, fast ramping machines, slow ramping machines, pulsed machines, and constant-power power supplies.

1 Introduction

During the last 50 years many accelerators have been built around the world. During this time power electronics has seen enormous developments in technology and performance. The electrotechnical basics, however, remain the same, independent of the actual technology of the semiconductor devices. The tendency to use more switched-mode power supplies continues. In the co-evolution of semiconductors and power supplies the voltage and current ratings and power densities have increased.

Technologies using high-power semiconductors like SCRs (Silicon Controlled Rectifier = thyristor) or power diodes in line-commutated topologies should be taken into account for new designs because of their simplicity and low prices.

As a guide to designers, an overview of the different technologies used in different machines will be shown here. The aim is not to go into the technical details of each power supply as has been done already in other contributions but to give an overview of what is currently installed in machines worldwide. Because of the large number of laboratories and machines only a fraction of the applications can be mentioned here.

Power supplies are categorized according to their function as follows:

- cycling machines
- fast-ramping machines
- slow-ramping or DC machines
- pulsed machines
- constant-power power supplies.

Corrector power supplies are excluded; the variety of installed technologies would fill a talk by itself and exceeds the bounds of this one.

2 Technology

2.1 High-power power supplies

Obviously SCR power supplies are still very common because of the good prices of these units. These units are generally used above 300 kW. If there is not a hard specification towards ripple, a standard 6 or 12 pulse power supply with LC filter is well suited, as in most of the PETRA and HERA SCR power supplies. For higher demands on ripple a ‘Praeg-filter’ (2-pole filter) can be introduced. This filter is named after the engineer who first described it. The capacitance is divided into a damped and an undamped part. In this way the damping of the higher frequencies is significantly higher with the price still low and without additional electronics. Filters of this type are in operation in the PETRA and HERA electron dipole power supplies, at Fermilab in the Tevatron and Main Injector, and in CERN SPS supplies.

For very high performance on ripple, suppression of grid distortion and regulation dynamic active filters are installed. The ripple of the power supply is suppressed over a broad bandwidth by an additional active part generally consisting of a transistor amplifier. Linear regulators are mainly used but switched-mode power supplies do exist as well. However, the high performance also has its drawbacks. These are the higher installation costs and the potential source of additional failures. The protection of the active filter may cause problems. So one should be sure that the active filter is really necessary.

2.2 Medium-power power supplies

For medium power usually up to approximately 300 kW, switched-mode power supplies become very common. These are either commercially available or special devices, developed by the labs themselves. The advantages of smaller volumes and very good regulation dynamics are obvious. The smaller volumes result from the better use of the magnetic material at high frequency, the higher power density in the semiconductors and smaller filters due to the higher corner frequency. The variety of different possible technical solutions is high, e.g., soft switching, hard switching, PWM, frequency shifting, etc. Recently soft switching technologies have become more interesting mainly for reasons of electromagnetic compatibility (EMC).

2.3 Regulation

The regulation in older machines is analog. However, digital regulation is becoming more common. Some accelerators which have been using digital regulation for power supplies for a long time are the CERN AD, RHIC and SLS. At DESY digital regulation has been introduced for the VUV-FEL. The LHC power supplies will use it as well.

3 Cycling machines

After production of the particles and first acceleration in linear accelerators, the particles are injected into a booster synchrotron. These are cycling machines operating at frequencies in the range of 0.5 Hz to some 10 Hz. The operation of these machines must not disturb the feeding mains more than allowed by the European standards EN 61000. The power supplies have to deliver the power at these frequencies with high accuracy. At these operation frequencies special care for the current sourcing grid has to be taken since these frequencies are in the range of the flicker frequencies. Power variations, especially changes in reactive power, lead to voltage changes whereby even small changes in the grid voltage amplitude cause problems. The resulting voltage variations cause changes in the intensity of electric lights. The human eye is very sensitive to these disturbances. The perceived flicker is very annoying.

There are different ways to counter these effects. The most commonly used circuit is the so-called 'White circuit', named after the engineer who first described it. Here the energy is stored in a resonance circuit consisting of the magnet inductance and capacitors. Via a second parallel resonance circuit with capacitor and transformer, the so-called White choke, the energy is supplied into the system. By this only the losses, being the dissipated energy in the resistive part of the magnets, are fed into the machines which are much lower than the cycling power needed. The power supplies can be designed to be much smaller. There are also lower energy costs. Because of the overall lower consumption the disturbances to the mains are less. The White circuit uses two power supplies: a DC supply and an AC supply. The basic diagram is shown in Fig. 1. The DC supply provides a bias current to ensure that the sum of both currents is always positive.

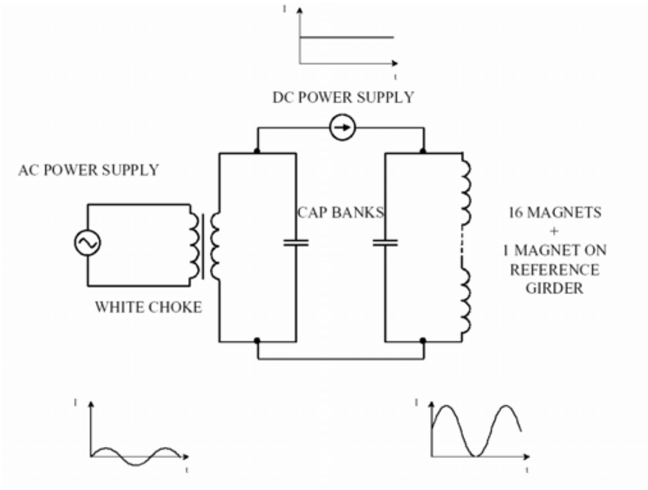


Fig. 1: White circuit

To show the difference in power consumption with and without a White circuit, a calculation made for BESSY II is presented in Fig. 2.

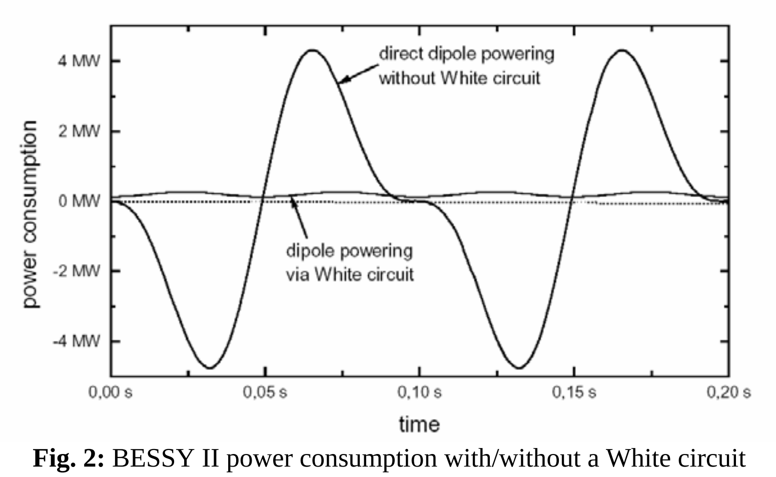


Fig. 2: BESSY II power consumption with/without a White circuit

3.1 DESY II

Depending on the age and the power of the machines, different types of power supplies are used. The oldest machine mentioned here is DESY II in Hamburg.

DESY II operates at a frequency of 12.5 Hz delivering electrons or positrons with energies of 4.5 GeV for the DORIS machine and 7 GeV for PETRA; 10 GeV is the maximum energy. The entire ring is divided into 12 resonating circuits to achieve lower voltages at the magnets as shown in Fig. 3.

This is a relic from the former operation frequency at 50 Hz. The voltage has been four times higher. The White choke is divided into 12 sections which are combined in one transformer oil tank (compound inductor).

Table 1: Values for DESY II

	Dipole	**QP**	**SP**
I_{max}	1170 A	1530 A	530 A
$I_{\text{rms magnet}}$	873 A	940 A	324 A
$U_{\text{rms choke/magnet}}$	4.3 kV × 12 = 51.6 kV	3.34 kV	273 V
$I_{\text{DC PS}}$	585 A	765 A	255 A
$U_{\text{DC PS}}$	27.7 V	122.4 V	32 V
$I_{\text{AC PS}}$	665 A	540 A	187 A
$U_{\text{AC PS}}$	990 V	3.34 kV	273 V

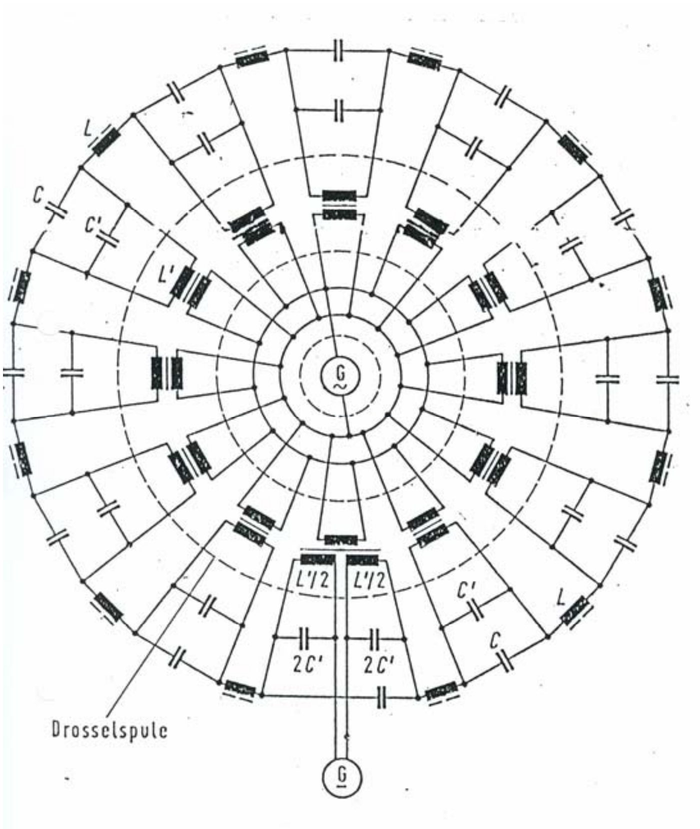


Fig. 3: DESY II overview

Three cyclo-converters are used in combination with a Steinmetz circuit for the AC part as shown in Fig. 4. This scheme suppresses the disturbances of the grid that would occur if only one modulated power supply was used. The Steinmetz circuit is usually used to put a two-phase load to a three-phase grid. Here the three-phase grid is modelled by adding a capacitive and inductive path to the White circuit. Because of the 120° phase shift of the cyclo-converters working at 12.5 Hz the grid perceives a constant load. For the DC power supply a 12-pulse SCR supply is used.

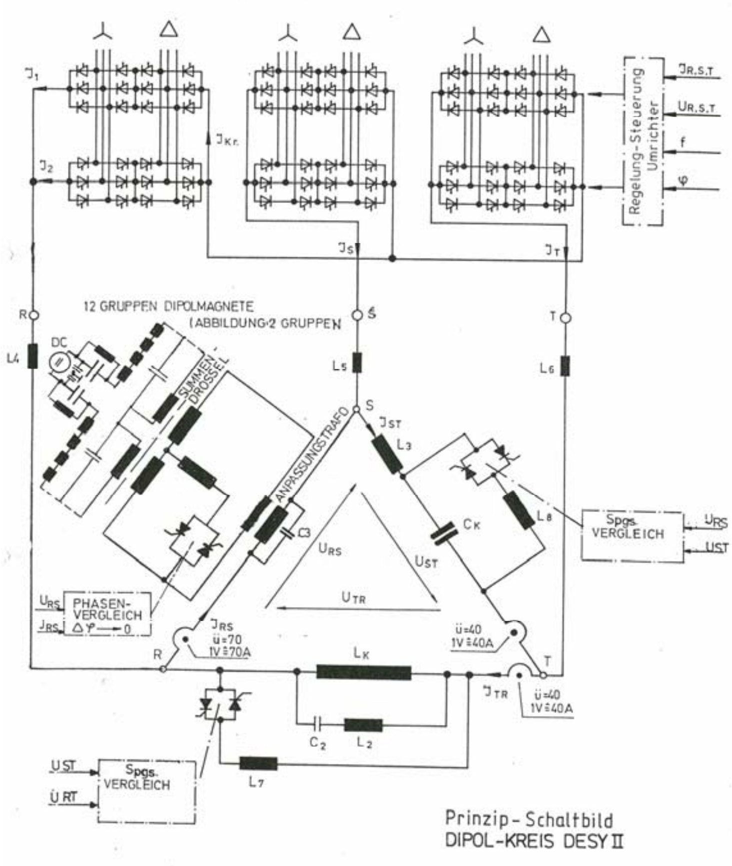


Fig. 4: DESY II power supply with Steinmetz circuit

3.2 ESRF

ESRF in Grenoble, France, also uses a booster ring with White circuit. It operates at 10 Hz with an energy of 6 GeV. For the power supplies, a switched-mode technology was chosen. It consists of an H bridge with GTO inverter and DC link as shown in Fig. 5. This power supply acts as current source inverter, using PWM. Figure 5 contains as well the current and voltage waveforms at different points of the power supply. All three power supplies for the dipole and the focusing/defocusing quadrupoles are built in the same manner.

Table 2: Values for ESRF magnet

	Dipole	QPF	QPDF
I_{max}	1600 A	500 A	500 A
$U_{\text{rms choke/magnet}}$	11 kV	2 kV	2 kV
$I_{\text{DC PS}}$	800 A	250 A	250 A
$U_{\text{DC PS}}$	580 V	270 V	270 V
$I_{\text{AC PS}}$	712 A	190 A	190 A
$U_{\text{AC PS}}$	535 V	302 V	302 V

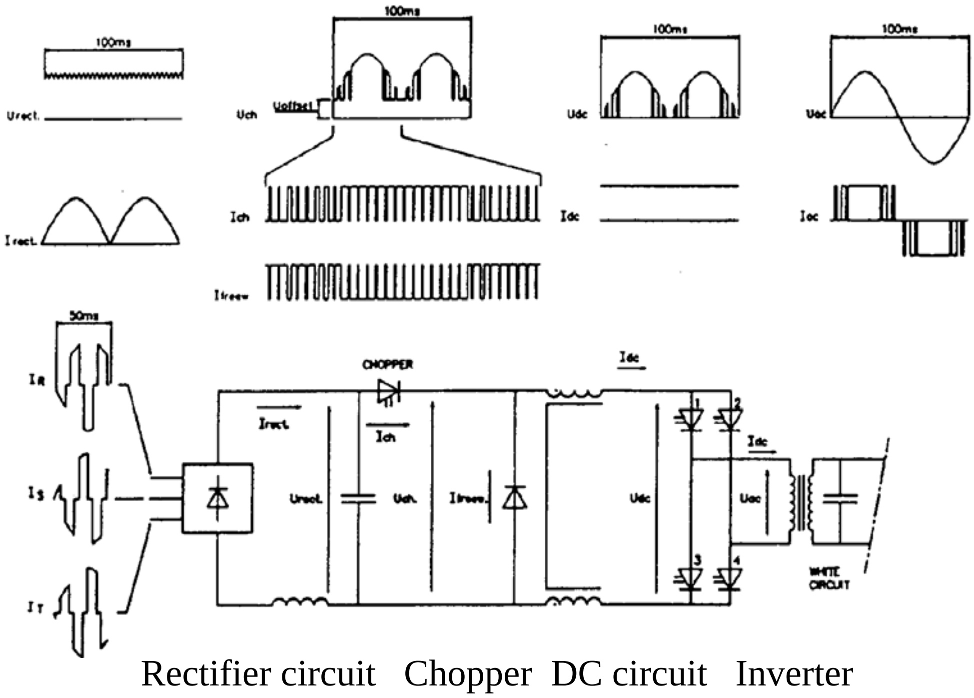


Fig. 5: Power supply of ESRF

3.3 BESSY II

BESSY II in Berlin Adlershof is mentioned as another institute having a White circuit and using a power supply with another technology. The booster accelerates to an energy of 1.9 GeV. BESSY II also uses a switched-mode power supply with a DC link. However, the power supply is now equipped with IGBT working in an H bridge. The switching frequency is 20 kHz. The schematic including the regulation scheme is shown in Fig. 6.

Table 3: Values for Bessy II magnets

	Dipole	**QPF**	**QPDF**
I_{max}	2277 A	492 A	395 A
$U_{\text{rms choke/magnet}}$	3112 kV	527 V	423V
$I_{\text{DC PS}}$	800 A	200 A	180 A
$U_{\text{DC PS}}$	120 V	70 V	70 V
$I_{\text{AC PS}}$	778 A	200 A	200 A
$U_{\text{AC PS}}$	311V	184 V	184 V

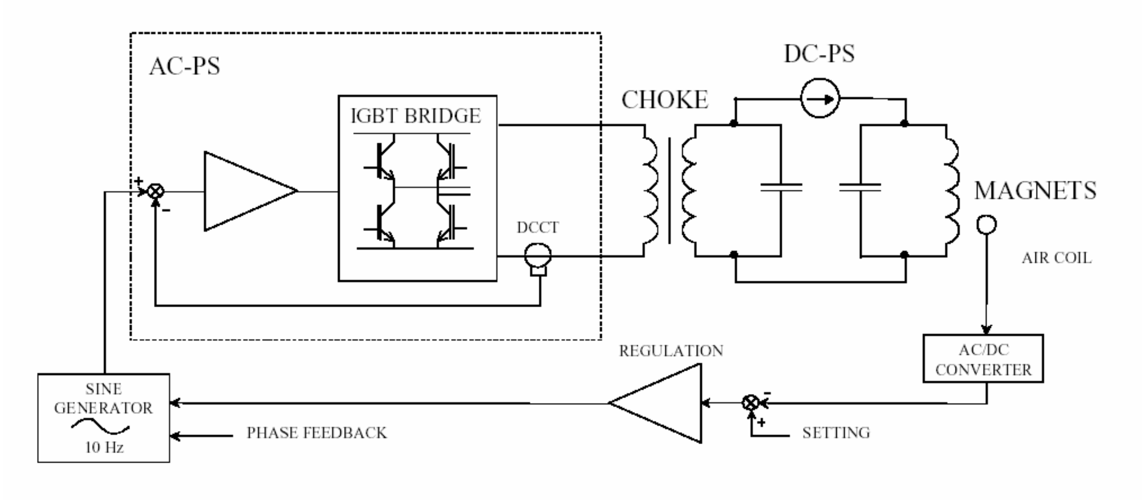


Fig. 6: Schematic of the BESSY II power supply

3.4 Slow-cycling machines

For machines with low cycling frequencies solutions are available without the White circuit. Examples are ANKA (Karlsruhe, Germany with 1 Hz, 500 MeV) and the Swiss Light Source (PSI, SLS, Villigen, Switzerland). Here the energy is no longer stored in magnetic devices but in capacitors. This is possible on account of developments in capacitor technology. Additionally a chopper for loading the DC link was introduced in order to decouple the accelerator from the grid. Figure 7 shows the principle of the SLS power supply. It was developed in-house and is a switched-mode unit, working with a digital regulation based on DSP/FPGA technology.

The third possibility to store energy in a rotating machine was used for the AGS Booster Synchrotron at Brookhaven National Laboratory, New York, which operates at 0.3 Hz to 7.5 Hz. This machine takes the energy for the machine directly from the grid.

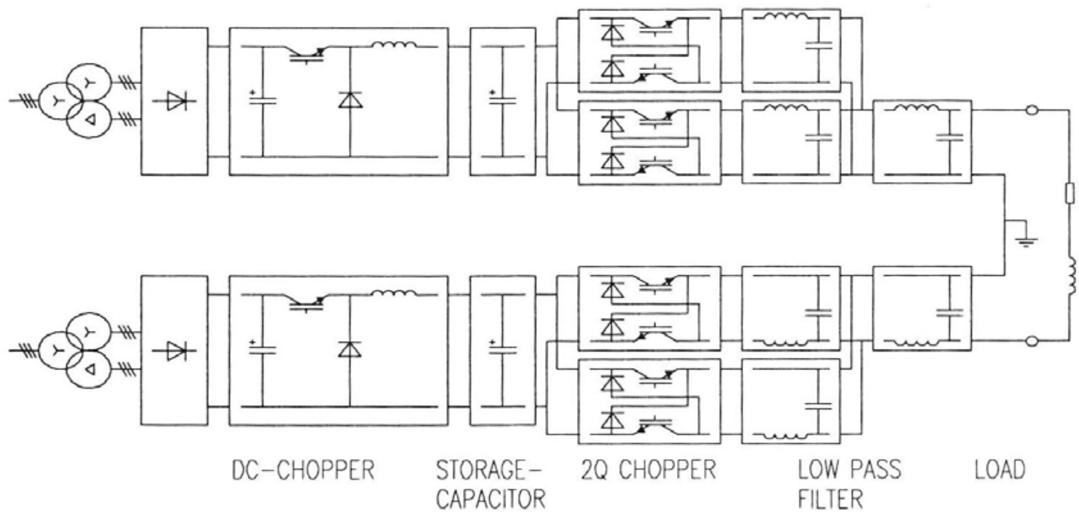


Fig. 7: Power supply at SLS

4 Fast-ramping machines

Fast-ramping machines have short ramping times which last for just one second up to one minute. The voltage of a magnet load is

$$u = R*I + L*\mathrm{d}i/\mathrm{d}t \quad (1)$$

Because of the term $L*\mathrm{d}i/\mathrm{d}t$, the voltage during ramping is significantly higher than during steady state. Additionally, for the down ramping, negative voltage has to be applied as well. As example for this the waveforms of DESY III are shown in Fig. 8 in an oscilloscope plot.

4.1 DESY III

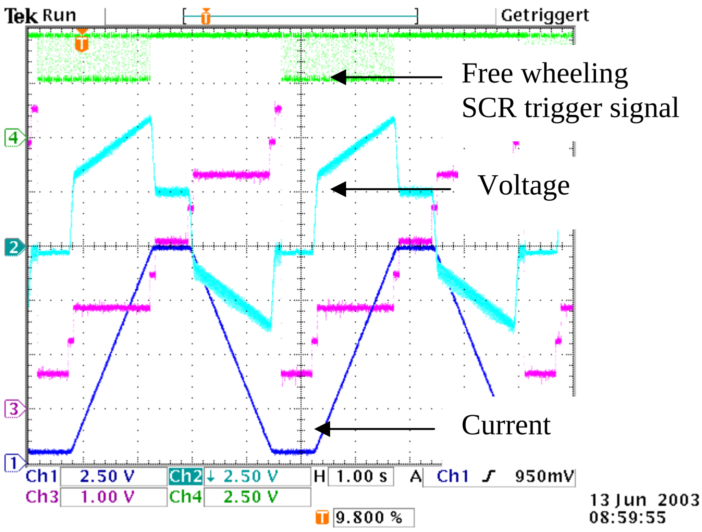


Fig. 8: Waveforms of DESY III

Table 4: Values for DESY III

	Dipole
$I_{\text{flat top}}$	1160 A
$U_{\text{flat top}}$	1 kV
$I_{\text{flat bottom}}$	50 A
$U_{\text{flat bottom}}$	42 V
di/dt	792 A/s
Ramping time	4 s

The entire cycle lasts 4 s (1.4 s ramp up, 0.6 s flat top, 1.4 s ramp down and 0.6 s flat bottom for injection). The power supply used is a 12-pulse SCR supply with a SCR as freewheeling path that is triggered during the flat bottom and ramp. It acts like a freewheeling diode. Thus the harmonic content is lower. The schematic including the reactive power compensation is given in Fig. 9. To achieve the negative voltage, the freewheeling SCR has to be turned off by turning off the firing signal. Since it is not leaking any current during the flat top it is off immediately. To lower the flat bottom harmonic content, a DC power supply of low voltage is installed in series to the main power supply. It delivers power during injection.

This voltage range from full negative to full positive leads to a large power variation in real and reactive power. Without any further precautions these variations would disturb the grid in an unacceptable manner. For DESY III active and passive reactive power compensations are installed. The dynamic compensation consists of a second 12-pulse power supply with equal nominal power being connected to a choke. This power supply is driven in opposition to the magnet power supply. When the magnet current is low this power supply delivers full current and vice versa. In this way the total reactive power is kept constant. Figure 9 shows the entire assembly. The overall reactive power at DESY is compensated by passive filters with resonance frequencies of 250 Hz, 350 Hz, 550 Hz, and 650 Hz.

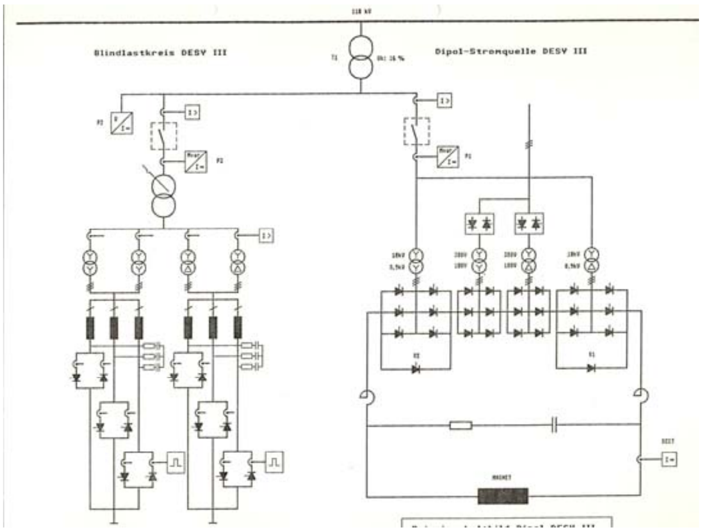


Fig. 9: DESY III power supply with active compensation for reactive power

The regulation for DESY III is analog. Different signals are transmitted from the control system to achieve a better wave form. The reference value for the current already contains a term to compensate for the eddy currents in the vacuum chamber. There is a soft start introduced between the flat bottom and the ramp-up plus a soft stop between ramp-up and flat top. This soft start/stop is a third-order function. Additionally the first, second and third derivatives of the current reference value are coupled into the circuit to compensate the tracking error and overshoot of the PI regulator during the cycle.

4.2 Tevatron/Main Injector

Other fast ramping machines include the Tevatron and the Main Injector at Fermilab, Chicago. The Tevatron is both a fast ramping machine and a storage ring. The circuit diagram is shown in Fig 10.

Table 5: Values for Tevatron

	Dipole
$I_{\text{flat top}}$	4400 A
$U_{\text{flat top}}$	1 kV
$I_{\text{flat bottom}}$	400 A
$U_{\text{flat bottom}}$	42 V
di/dt	67 A/s
Ramping time	60 s

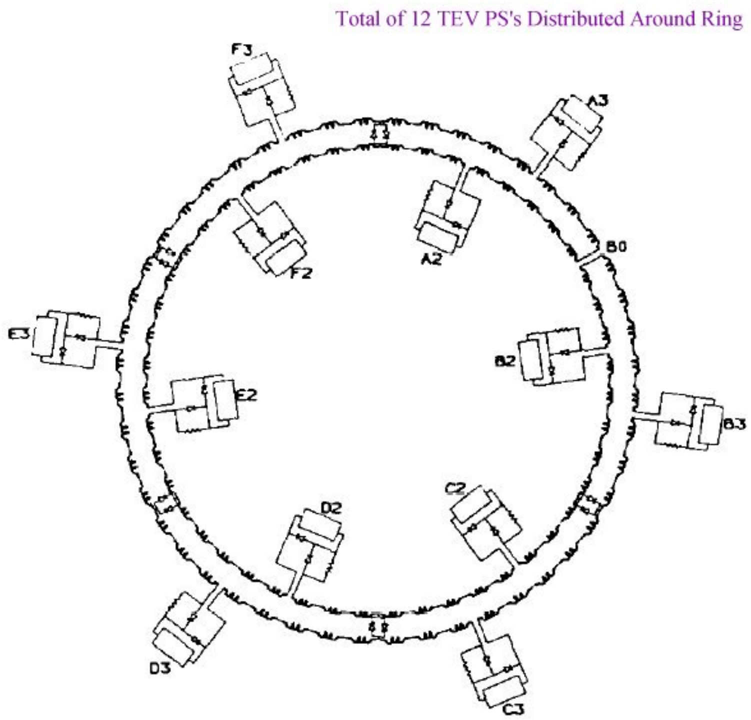


Fig. 10: Tevatron distribution of power supplies

Here it is not one ramping supply that is used. The ramping is done with 10 power supplies having ±3000 A_{rms} and ±850 V and two having 500 A and ±850 V. These are distributed over the entire ring to have a low voltage towards ground. The ramping time is 60 s. During steady state only two power supplies are needed to compensate the ohmic losses in the circuit. The other power supplies are bypassed by SCRs which are used as freewheeling paths that can be triggered. For the down ramping these SCRs have to be turned off. The technology is 12-pulse SCR with Praeg filters and an additional 120 Hz trap.

The same principle is used for the newly commissioned Fermilab Main Injector (FMI) shown in Fig. 11. However, the ramping times are significantly shorter. There are three different operation modes: from injection at 8.9 GeV to 120 GeV for Antiproton Source stacking (1.5 s), 150 GeV Tevatron injection (2.4 s, 9.4 kA), and 120 GeV slow spill operation (5.4 s). The maximum d*i*/d*t* is 14 kA/s.

The power supplies have a rating of 5000 A_{rms} and 1 kV each. They are built as 12-pulse SCR units with a Praeg filter for 120 Hz suppression and additional traps at 240 Hz, 360 Hz and 720 Hz. As already mentioned the power supplies can be bypassed by a SCR. The power supplies are switched on and off according to the required voltage. The total power change during the ramping is 120 MVA and 21 MW.

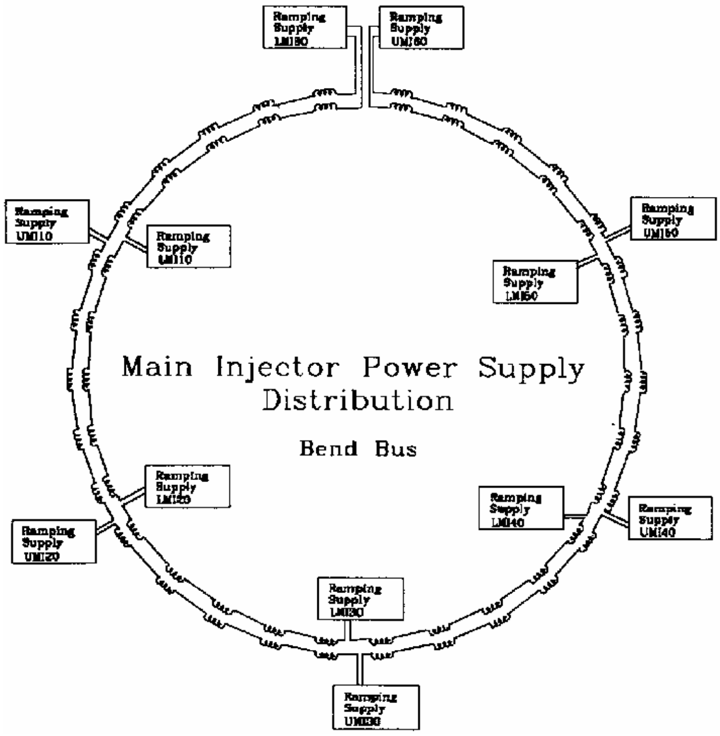


Fig 11: Fermilab Main Injector

Table 6: Power requirement for FMI

Requirement	
Dipole and quadrupole power, peak	120 MVA
Dipole and quadrupole power, average	60 MVA
RF, beam line power supplies, peak	30 MVA
RF, beam line power supplies, average	20 MVA
Backfeed capability, peak	40 MVA
Backfeed capability, average	30 MVA
Accelerator cycling time	1.5 s

4.3 CERN

CERN has several fast-ramping machines including the SPS, the PS, and the new Antiproton Decelerator (AD). In the latter, antiprotons are injected at 3.57 GeV, cooled, and decelerated to 100 MeV. One cycle takes about 60 s having different intermediate stages as shown in the *U*/*I* diagram of Fig. 12. The 12-pulse SCR power supplies of the former Antiproton Collector have been upgraded with an active filter. For the active filter a switched-mode power supply was chosen. Figure 13 shows the power part of the rectifier and the active filter.

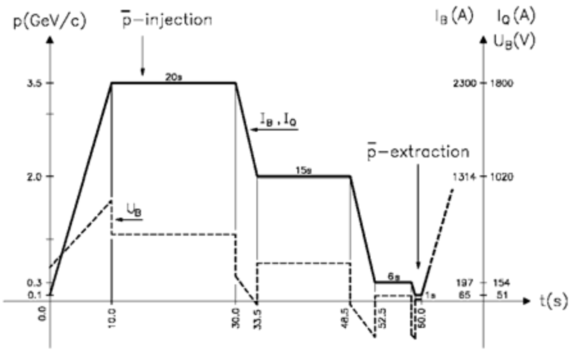


Fig. 12: CERN Antiproton Decelerator cycle

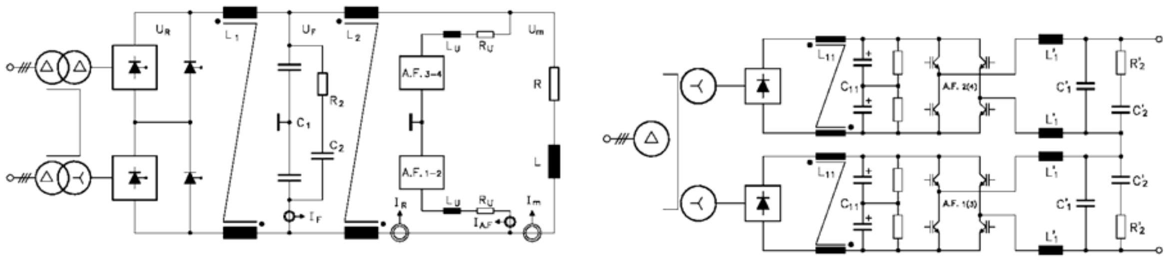


Fig. 13: Power supply for the Antiproton Decelerator (left) plus active filter power supply (right)

4.4 PS Booster beam transport line

For the PS Booster beam transport line new switched-mode power supplies have been installed. These are four-quadrant, switched-mode power supplies.

Figure 14 shows the schematic. The power supply switches at 18 kHz, delivering a current of 0 A to 450 A with a voltage of 0 V to 550 V. The required settling time to an accuracy of 100 ppm is 750 ms with a magnet having a time constant of 925 ms. This power supply consists of a diode rectifier, three H-bridge IGBT converters, and a rectifier at the secondary side with passive filters. To reverse the currents an SCR polarity switcher is used. Additionally a regenerative circuit is built in. The energy fed back by the magnet is stored in a capacitor. From here it is inverted back into the grid via a 6-pulse SCR bridge and transformer. The diagram is shown in Fig. 15.

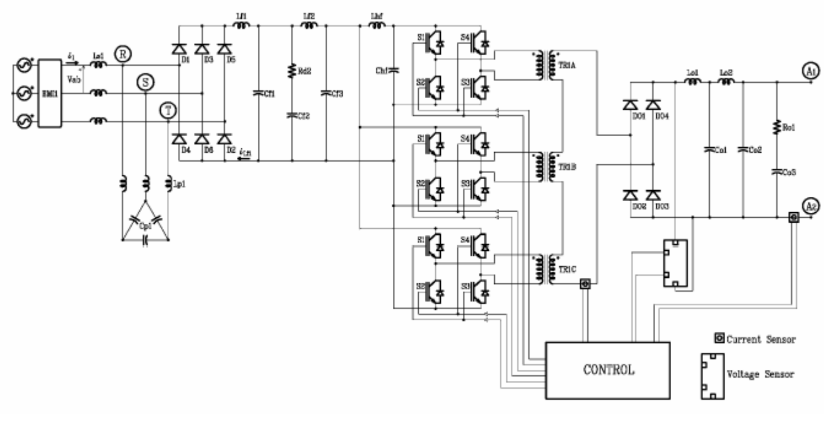


Fig. 14: Power supply for the PS Booster beam transport line (Part 1)

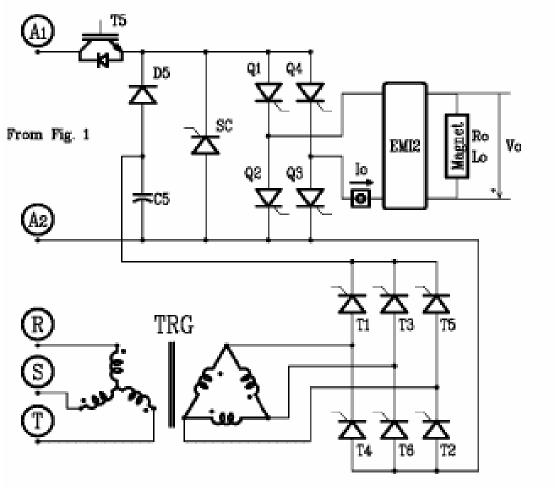


Fig. 15: Polarity switcher with regenerative circuit

4.5 PETRA

For PETRA one entire magnet cycling lasts 1 min. Again, to decrease the voltage to ground, the power supplies are divided into three different units. The circuit diagram is shown in Fig. 16. The regulation is analog. In order to keep the reactive power low, the power supplies are driven one after the other: when one power supply has reached maximum voltage the next power supply, waiting at a minimum current, starts. Even so this machine has enormous impact on the voltage of one sector of the DESY grid. The effect is shown in Fig 17. The different stages of machine fillings are illustrated significantly on the voltage measurement.

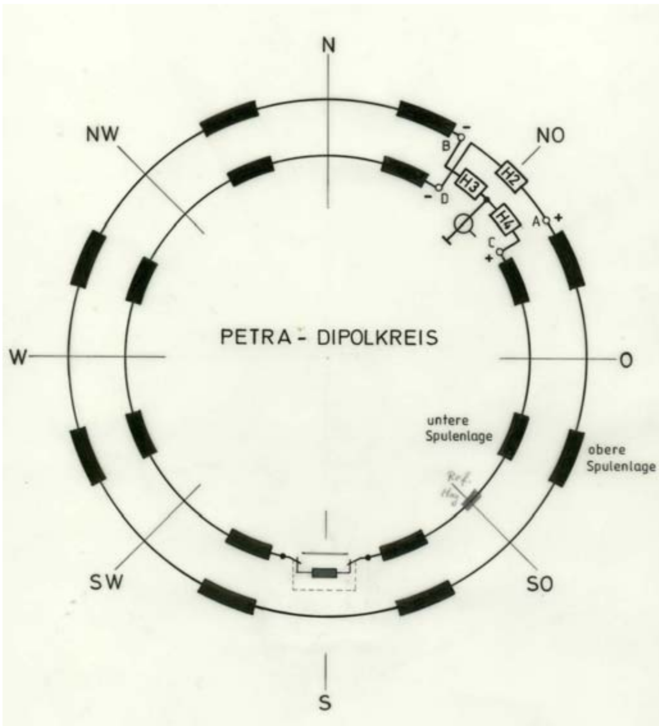


Fig.16: The PETRA dipole ring

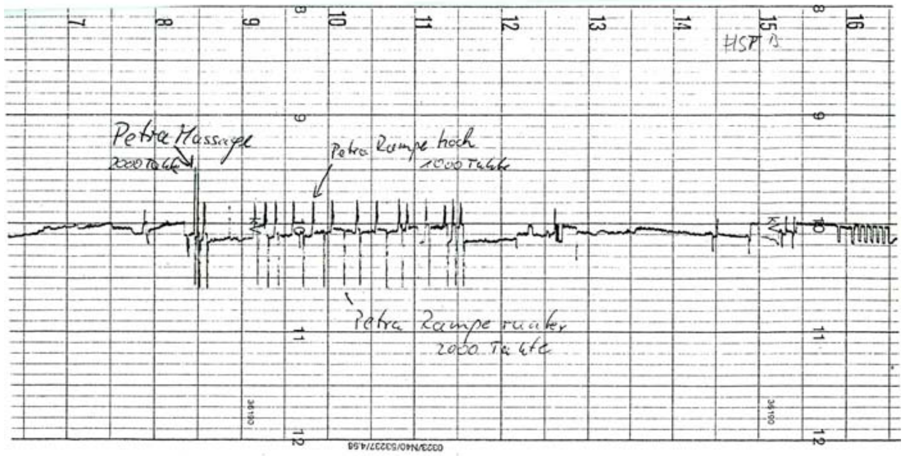


Fig. 17: Voltage changes due to the ramping of the PETRA machine (voltage [kV] over time [h]

5 Slow-ramping or DC machines

Most accelerators belong to this category. These machines are either permanently at steady state like the synchrotron light facilities or are ramping very slowly for several minutes. Here the variety of different power supplies is huge and shows in general the actual state of the art of switched-mode power supplies at the time the machines were built.

5.1 HERA

The HERA machine consists of two magnet rings namely the superconducting ring for protons and a normal conducting ring for electrons. A variety of different technologies is installed. The main dipole rings have 12-pulse SCR power supplies. The unit for the proton dipole circuit has an active filter, see Fig. 18. The specification of the supply is 8000 A nominal with 5600 A current at luminosity. The voltage is +500 V to –300 V to allow a ramping down of the superconducting ring.

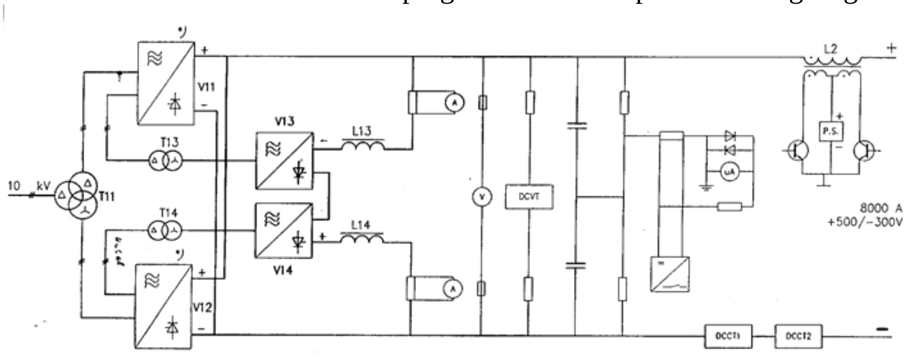


Fig. 18: Power supply for the HERA proton dipole magnet ring

The PS with active filter for the electron dipole is capable of driving 8000 A at a voltage of +500 V. For the storage ring with normal-conducting magnets no negative voltage is necessary. The power supplies with the following data P > 50 kW, I > 800 A or U >130 V are built as 6- or 12-pulse SCR power supplies including conventional LC filters. For lower values buck converters are installed. There are about 570 units with nominal currents in the range of 60 A to 400 A and voltages up to 130 V. The primary DC voltage is delivered by means of a central B6-diode rectifier that supplies up to 16 switched-mode supplies. The power supplies are equipped with mechanical polarity switchers to be able to reverse the current in the magnet load. However, there are restrictions on the driving speed during the zero crossing. Therefore for a power up to 10 kW (±100 A/ ±100 V) bipolar power supplies with a hard switching H bridge are in use. Prototypes of ±200 A/200 V are under development. The switching frequencies of all chopper power supplies at HERA are set to 15.7 kHz. This corresponds to the 1/3 resonance of the betatron frequency of HERA. This guarantees that the chopper frequency does not conflict with the beam betatron frequency. Figure 19 shows the schematic of the converter.

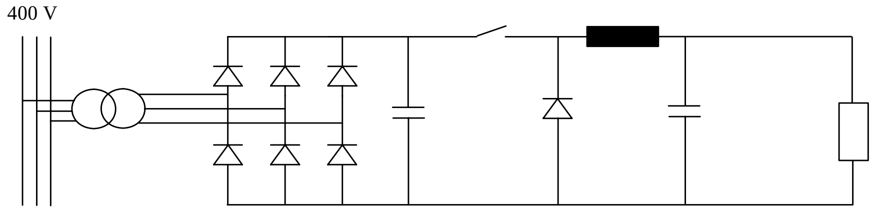


Fig. 19: Buck converter

5.2 LEP

At CERN switched-mode power supplies have been in operation for a long time. A large number of switched-mode supplies were installed in LEP. These were of the double-resonant converter type having a power of 37.5 kW as shown in Fig. 20. These power supplies were able to deliver 125 V/300 A, 188 V/200 A or 250 A/150 V.

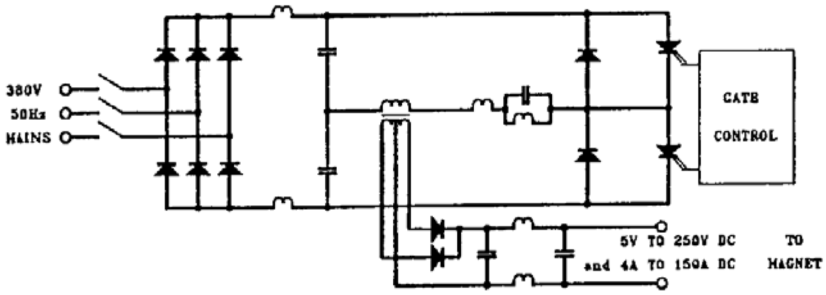


Fig. 20: Schematic of the LEP double-resonant power supply

5.3 LHC

New developments at CERN are being made for the power supplies for the Large Hadron Collider (LHC). Here different types of supplies have been developed in switched-mode technology. One new approach is the use of the zero-voltage/zero-current switching technology. Figure 21 shows the schematic of the 600 A/10 V or 40 V supply. The voltage is rectified by a diode rectifier and filtered by a passive LC filter with 40 Hz resonance frequency. The actual switching unit consists of a 'Full-Bridge, Zero-Voltage Zero-Current Switching, Phase-Shift inverter' (FB-ZVZCS-PS inverter) operating at a frequency of 30 kHz, the high-frequency transformer, rectifier stage and a fourth-order LC output filter. Finally there is a Bipolar Linear Output Stage (BLOS). This stage has several functions. It is used for supplying and discharging the coils of the superconducting correction magnets with high-precision current. It must guarantee a very precise zero-crossing of the current. The energy stored in the magnet is dissipated in the BLOS. Finally it leads a constant bias current through both halves of the stage. Thus the soft zero-crossing is possible without discontinuity (Fig. 22).

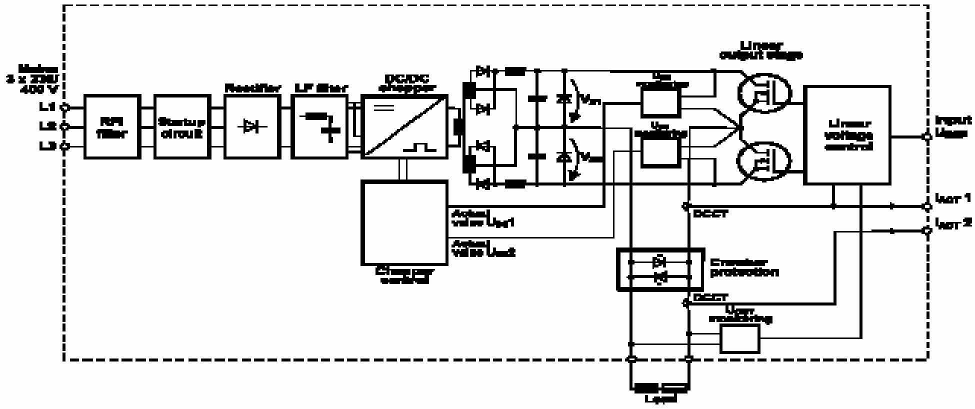


Fig. 21: LHC ±600 A, ±12 V, power supply

Overall more than 1700 new power supplies will be installed for the LHC. Power supplies in SCR technology with active filters will be used. These have quite impressive values such as 13 kA, 180 V or 6500 A, 950 V. These units will not have a series transformer for the active filter but use the principle of capacitor injection as shown in Fig. 22.

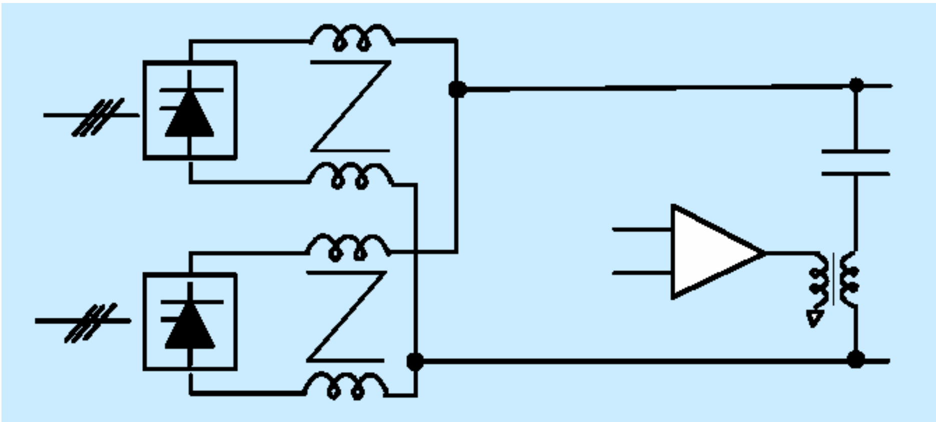


Fig. 22: SCR unit with active filter for the LHC

6 Pulsed machines

6.1 VUV-FEL, XFEL

At DESY the XFEL will be built as a European synchrotron radiation facility. This machine will consist of a 1.5 km long superconducting linear accelerator in TESLA technology delivering electrons with an energy of 20 GeV. It includes three SASE and two spontaneous undulators. This will be a pulsed machine operating at 10 Hz repetition rate. The pulse length will be 1.5 ms.

The power supplies are divided into magnet power supplies and capacitor loading supplies for the modulators and are described below.

6.2 Magnet power supplies

Despite the fact that the machine is pulsed, the magnet power supplies will be steady state for reasons of accuracy and simplicity. If the power supplies are switched on and off with 10 Hz, mechanical vibrations in the magnet structure might occur. For efficiency and space reasons the power supplies have to be installed inside the tunnel. The access period is foreseen to be only one day every four weeks. Therefore these power supplies have to be very reliable. To fulfil this demand for reliability a new type of power supply was developed for this purpose. The power supply has built-in redundancy by a modular approach. The power part is divided into modules and $n + 1$ modules will be installed; n being the number of modules required for the nominal current of the power supply. One module is installed additionally and can take over in case of trip. Special emphasis was put onto the controls. On account of the limited access, the maintenance crew is interested in having a lot of information about the status of the power supplies. One interface is for the maintenance crew via the Internet. By means of a standard browser, about 60 different signals including a scope function are displayed. In case of failure 64 signals are sent by email; these include parameters, current and voltage measurements, ripple values, temperature and delay times. The second interface for the control room is done with CAN bus/Ethernet. The regulation of the power supply is digital based on a FPGA. The nominal data of the supplies are up to 100 A/10 V. The power parts consist of five power modules each being able to carry 25 A.

Figure 23 shows the schematic of the power part. The power supply has a 2-phase AC input. Each module has its own diode rectifier and LC filter. The power supply is switched on the primary at a frequency of 25 kHz. For the secondary the rectifier and polarity switcher are combined using the same MOSFET switch. Because of the low stray inductance of the transformer the current decreases very fast in the primary. Therefore the power supply is a zero-current/zero-voltage switching power supply. To minimize switching losses the circuit has a variable switching frequency of 0 Hz to 50 kHz and a variable pulse width of 0% and 50%. Primary and secondary are switched as shown in Fig. 23.

For the VUV FEL a series of 65 of these units will be installed. After series production in the year 20004, 43 power supplies have proven their reliability and benefits in the first stage of the VUV FEL.

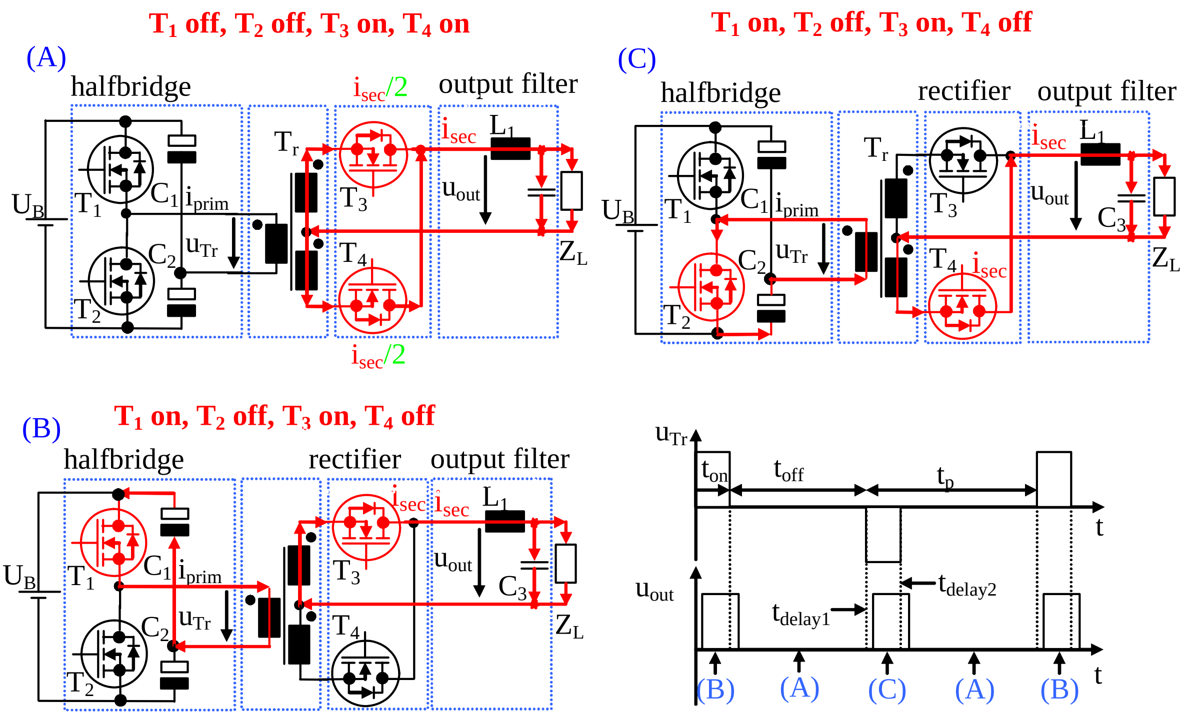


Fig. 23: Magnet power supply for superconducting quadrupoles

6.3 Constant-power power supplies/power supply for modulators

The second type of power supply is used for loading the capacitor bank of the modulators (Fig. 24). The modulator consists of a main capacitor bank, a so-called bouncer circuit being a resonant circuit of an inductor and capacitor, a semiconductor switch, and a pulse transformer. The switching is done on the medium voltage side at approximately 10 kV. This voltage is then transformed to the 120 kV level. The capacitor bank is used to deliver the energy during the pulse to the klystron. During the pulse of 1.5 ms the capacitor voltage droops about 20%. The power supply smoothly charges the capacitor with constant power to keep the low-repetition-rate pulses from disturbing the mains. Two different types of power supplies have been investigated and installed to fulfil this purpose.

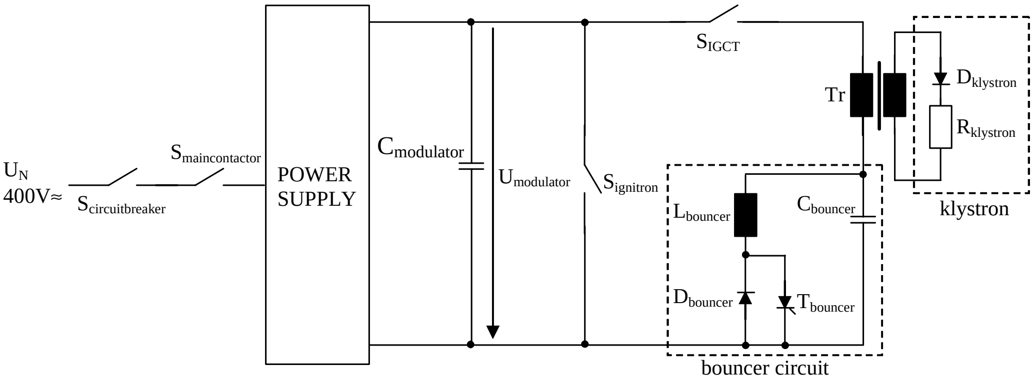
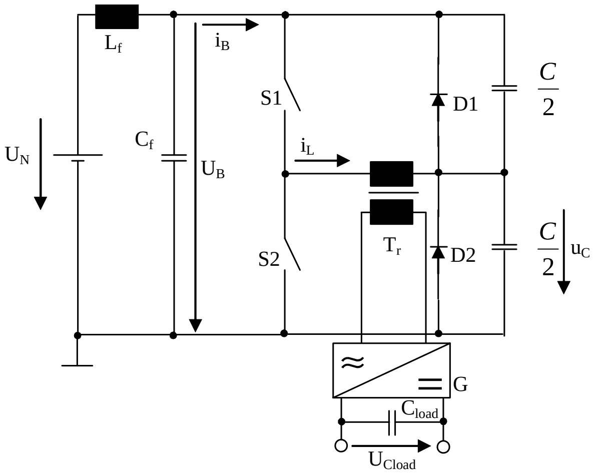


Fig. 24: Schematic of the modulator

One power supply was developed at DESY. Owing to the principle of the circuit, the power supply delivers constant power at a given frequency. A power regulation adjusts the frequency in order to reach the desired voltage at the capacitor at the moment of the pulse trigger. The schematic is shown in Fig. 25. Another power supply (Fig. 26) is a series connection of buck converters. Sixteen converters are stacked to achieve the 12 kV maximum voltage of the capacitor bank. This power supply was bought from industry. A digital self-learning regulation also based on FPGA was developed to ensure the accuracy of the capacitor voltage at the moment of pulsing as well as the suppression of the repetition rate towards the grid.



G	Rectifier
i_B	supply current
i_L	primary current of the transformer
u_C	voltage of the resonance capacitor
U_{Cload}	output voltage to the switch of the klystron
i_{Bt1}	current i_B at the time t1
L	primary stray inductivity of the transformer
f	resonance frequency of the resonant circuit of L and C
n	gear ratio of the transformer and rectifier
T	period time of the switching frequency of S1 and S2
C	resonance capacitor
U_B	supply voltage
U_N	line voltage
C_f	filter capacitor
L_f	filter inductance

Fig. 25: DESY constant-power power supply

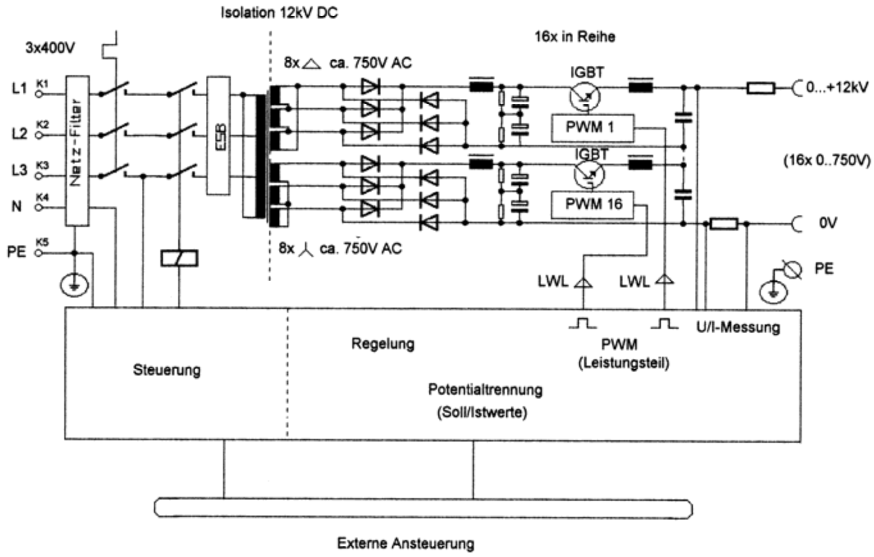


Fig. 26: Constant-power power supply

7 Summary

Many different solutions for solving the power supply specifications of accelerators have been found. A brief overview of power supplies installed in the world is given here. This should be helpful for engineers if new specifications arise and should help in knowing who might be asked for assistance or advice.

There is still a large field for future developments. Further improvements will doubtless be achieved with the switched-mode technologies.

Of special help for engineers in the power supply departments of accelerators is the Web page of the ‘Joint Accelerator Conferences Website’ (http://accelconf.web.cern.ch/AccelConf). A large number of publications about power supplies can be found there.

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