Chapter 9

POWER SUPPLIES

9.1 Introduction

The storage ring power supplies, with the exception of the injection elements are DC supplies. All the new power supplies are rated for 2.5GeV operation plus 10-15% safety guard for both current and voltage. The storage ring consists of 16 dipole magnets, 32 quadrupoles, 64 sextupoles and 64 correction power supplies. The dipole, quadrupole and sextupole power supplies are all unipolar as opposed to the correction power supplies, which are 4-quadrant to allow reversal of the current through the load if necessary. Since the particles will be accelerated in the storage ring from 800MeV to 2.5GeV, the DC power supplies should be able of providing the magnets with a ramping current, which is proportional to the energy of the particles.

In the booster synchrotron, the particles are accelerated from 22.5MeV to 800MeV. The booster consists of 12 dipoles, 12 focusing and 6 defocusing quadrupoles comprising 3 families of magnets and supplies by 3 separate switched-mode power supplies with a repetition frequency of 1Hz (the BESSY I booster was operating with 10Hz).

9.2 Storage Ring Power Supplies

The storage ring consists of 16 dipole magnets, which are connected in series and powered by one power supply. The quadrupoles are divided into two focusing families. Each family consists of 16 series-connected magnets and is powered by a separate power supply. There will be no defocusing quadrupole used in this design as the defocusing function is accomplished by the windings mounted on the poles of the dipole magnets (pole-face-windings). The pole-face-windings are connected in series and powered by one power supply. The 64 sextupole magnets are divided into 2 focusing and 2 defocusing families, each consisting 16 magnets and powered by one power supply. The output currents of the DC power supplies, which are proportional to the instantaneous energy of the particles, increase from 32% to 100% of the peak value during the energy ramp from 800MeV to 2.5GeV. The current then stays at the flat-top level for several hours while the beam current is decaying with a life time of 1-20 hours. The magnets are de-energized during the negative ramp, which takes 0.5-3 minutes. The estimated time intervals of the positive/negative ramps are shown in Table (9.1).

Table 9.1: Storage ring ramping intervals

Storage ring	Time interval	Unit
Flat bottom	30-120	Sec
Positive ramp	60-120	Sec
Flat top	1-20	Hours
Negative ramp	30-180	Sec

9.2.1 Specifications of the Existing Power Supplies

The electrical specifications of the storage ring magnets, cables, optic demands and the existing power supplies have been summarized in Table (9.2). The power supply data in Table (9.2) are related to the BESSY I machine plus some comments on the use of SPEAR II power supplies, which could be available for SESAME.

Table 9.2: Electrical specifications of the SESAME storage ring and the existing power supplies from BESSY I and SPEAR II

	Magnets				Cabling					Optic				Power Supplies							Comments
	Family	Qty	L /magnet	R /magnet	Len.	Cross sec.	R /m	R total	Drop on cable	I max	U max	Pwr	Stab.	I max	U max	Pwr	Stab.	Type	Com.	Year	
Unit			mH	mOhm	m	mm^2	u Ohm	m Ohm	Volt	Amp	Volt	kW	ppm	Amp	Volt	kW	ppm				
Dipole:																					
	DS1- DS16	16	80	50.6	260	185*2	48.2	12.5	8	643	561.9	361	100	900	610	549	10	Uni.	Foeldi	1986	*BESSY I*: DIPPR BI and DIPPR BI (cosy) in series *SPEAR2*: 1400A/700V
QF:																					
	QFS1, QFS4, QFS5, QFS8, QFS9, QFS12, QFS13, QFS16, QFS17, QFS20, QFS21, QFS24, QFS25, QFS28, QFS29, QFS32	16	7.9	16.4	260	185	96.4	25.1	8.9	356	93.9	33	100	600	160	96	10	Uni.	Jager	1995	*BESSY I*: MDDB Neu BI
	QFS2, QFS3, QFS5, QFS7, QFS10, QFS11, QFS14, QFS15, QFS18, QFS19, QFS22, QFS23, QFS26, QFS27, QFS30, QFS31	16	7.9	16.4	260	185	96.4	25.1	8.9	356	93.9	33	100	400	83	33	100	Uni.	DAN	1993	*BESSY I*: S1 WLS *SPEAR2*: 800A/150V
SF:																					
	SFS1, SFS3, SFS5, SFS7, SFS9, SFS11, SFS13, SFS15, SFS17, SFS19, SFS21, SFS23, SFS25, SFS27, SFS29, SFS31	16	3.5	37.8	140	95	188	26.3	3.7	140	84.8	12	100								No suitable PS from BESSY I or SPEAR2
	SFS2, SFS4, SFS6, SFS8, SFS10, SFS12, SFS14, SFS16, SFS18, SFS20, SFS22, SFS24, SFS26, SFS28, SFS30, SFS32	16	3.5	37.8	140	95	188	26.3	3.7	140	84.8	12	100								No suitable PS from BESSY I or SPEAR2
SD:																					
	SDS1, SDS3, SDS5, SDS7, SDS9, SDS11, SDS13, SDS15, SDS17, SDS19, SDS21, SDS23, SDS25, SDS27, SDS29, SDS31	16	3.5	37.8	140	95	188	26.3	3.7	140	84.8	12	100								No suitable PS from BESSY I or SPEAR2
	SDS2, SDS4, SDS6, SDS8, SDS10, SDS12, SDS14, SDS16, SDS18, SDS20, SDS22, SDS24, SDS26, SDS28, SDS30, SDS32	16	3.5	37.8	140	95	188	26.3	3.7	140	84.8	12	100								No suitable PS from BESSY I or SPEAR2

There are some disadvantages associated with the use of the BESSY I power supplies; The dipole power supply from BESSY I are very old and need refurbishment; The voltage of the second QF power supply is less than the requirements; There is no suitable power supply to be used for the four families of the sextupole magnets. For these reasons, most of the BESSY I power supplies are considered unsuitable for the 2.5 GeV operation of SESAME. In these cases new power supplies should replace the old ones.

9.2.2 Specifications of the New Power Supplies

The specifications of the new power supplies and the magnets are summarized in Table (9.3).

Table 9.3: Specifications of the magnets and new power supplies

2.5GeV	Dipole	Quad.	Sext.	Unit	Sum
Total inductance (per circuit)	1280	126.4	56	mH	
Total resistance (per circuit)	809.6	262.4	604.8	mOhm	
Time constant	1.6	0.5	0.1	Sec	
Number of circuits	1	2	4		
Num. of magnets per circuit	16	16	16		
Inductance per magnet	80	7.9	3.5	mH	
Resistance per magnet	50.6	16.4	37.8	mOhm	
Temperature rise	15	15	15	Deg C	
Final current	643	356	140	A	
Initial current	205.8	113.9	44.8		
Maximum voltage	529.9	93.9	84.8	V	
Overall stability	100	100	100	ppm	
Max. active power	340.7	33.4	2.4	kW	417.1
Power supply nominal current	700	400	160	A	
Power supply nominal voltage	700	120	100	V	
Installed Power	490	48	16	kW	651.7
Transformer	617.4	60.5	20.2	kVA	819.2

The power supplies are rated for 2.5GeV operation taking 10-15% safety guard and the cable drops into consideration. The load on the main transformer has been calculated for 20% transformer losses and 5% voltage drops.

9.2.3 Power Converter Topologies

In this section principle schemes and operation of different power converter topologies, are explained and their performance and suitability of application are compared for the SESAME storage ring.

Three main power converter topologies are considered:

1. Linear power converter.
2. Line-commutated thyristor power converter.
3. Switched-mode power converter.

9.2.3.1 Linear Power Converter

These power converters were used extensively 30 years ago but since then their popularity has been declined because of the low efficiency and the number of incorporated magnetic components. Now, they are mainly used for noise-sensitive applications such as telecommunications and medicine [30].

The basic structure of a linear power converter is shown in Figure (9.1)

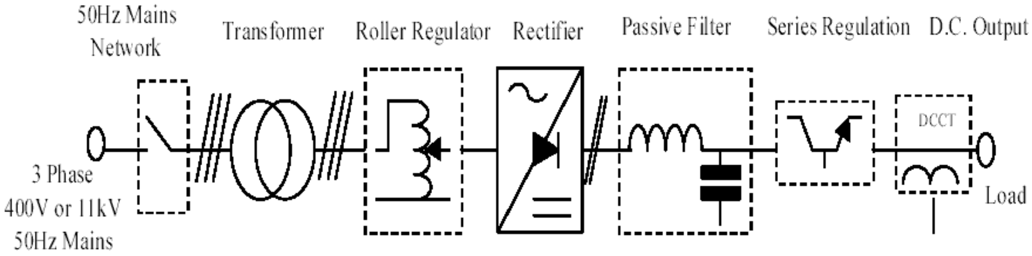

Figure 9.1: Schematic block diagram of a linear power converter.

A linear power converter consists of a transformer for isolation and impedance matching, a roller regulator for course adjustment of the voltage, a diode rectifier, a LC passive filter and a series regulator. The series regulator consists of a transistor bank working in the linear region. Regulation of the output voltage is accomplished by controlling the voltage drop on the series regulator, which is dependent on the base current of the transistors.

Since no switching element (i.e IGBT, thyristor) is needed, the noise level of a linear power converter is low. The power factor is close to unity and the bandwidth is high for small signal response.

The disadvantages of linear power converters include the size, which is significantly bigger than a switched-mode power converter and the low efficiency because of the power dissipation on the series regulator. The large signal response will be poor if a pre-regulator is used.

9.2.3.2 Line Commutated Thyristor Power Converter

This type of technology is extensively used for high power applications. The basic structure includes an input transformer, a 3-phase full bridge and a LC network forming the output filter. A simplified schematic diagram of a 6-pulse full converter is shown in Figure (9.2).

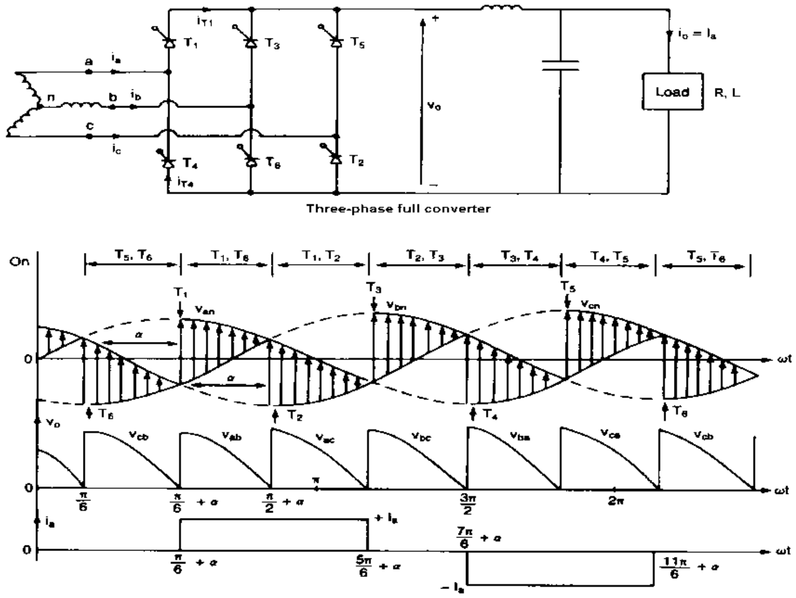

Figure 9.2: A simplified circuit diagram of a 6-pulse converter and the associated current and voltage waveforms.

The output voltage is the average value of the voltage waveform, which appears at the input of the LC filter. Control over the output voltage is accomplished by changing α, the firing angle of the thyristors. It can be shown through calculation that for a 6-pulse converter, the DC output voltage is proportional to the cosine of α. It can also be shown that the phase difference between the phase current and the phase voltage is equal to α. During the current ramp, the power factor changes because of the variations of α. In order to keep the power factor close to unity, reactive power compensation circuits may be necessary.

For higher output powers, a 12-pulse configuration can be utilized which comprises two 6-pulse bridges connected in series or in parallel to provide the required output voltage or current. The principle scheme of a 12-pulse configuration is shown in Figure (9.3) along with the current and voltage waveforms.

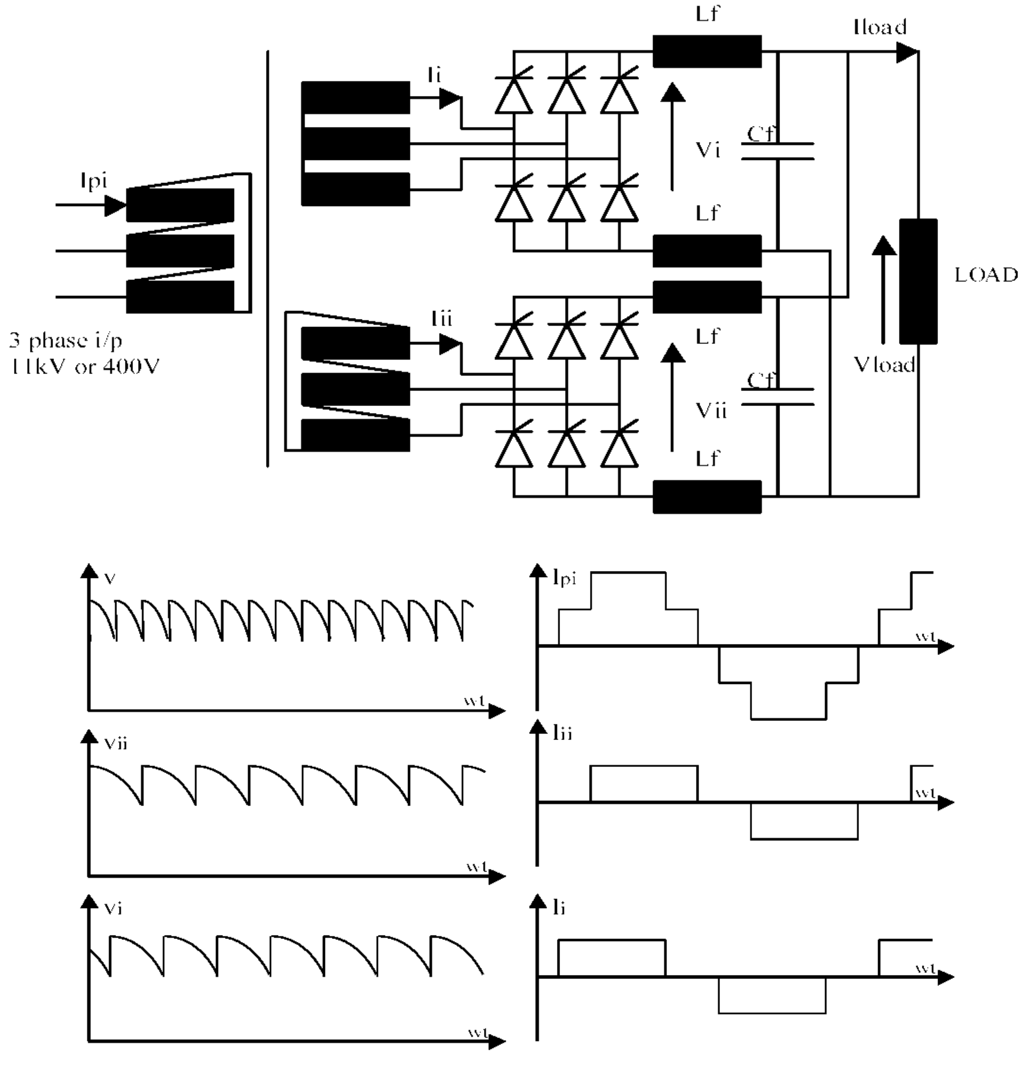

Figure 9.3: 12-pulse line-commutated thyristor power converter.

Connecting one of the transformer secondary windings in star and the other one in delta generates the 30 deg phase shift between the two bridges. This results in higher ripple frequencies and therefore reduced size of the LC filter. Compared to a 6-pulse converter, the phase current resembles more closely a sinusoid, which means improved harmonics of the input current.

The advantages and disadvantages of the line-commutated thyristor power converter could be summarized as follows [3]:

- The power factor is directly related to the thyristor firing angle and can vary between 0 and 0.8 during the operation. This will incur additional costs for power factor correction;
- Input current harmonics can be improved if 12-pulse (or higher) design employed;
- Produces thyristor firing-notches in the network and noise spikes, which may disturb other users;
- Large and heavy magnetic elements such as transformers and chocks make it unsuitable for low power applications;
- Bandwidth is dependent on the number of pulses and at best is moderate;
- Extensively used technology with competitive market;
- Simple design, minimal number of components, high reliability;

9.2.3.3 Switched-Mode Power Converter

A typical switched-mode power converter structure is shown in Figure (9.4)

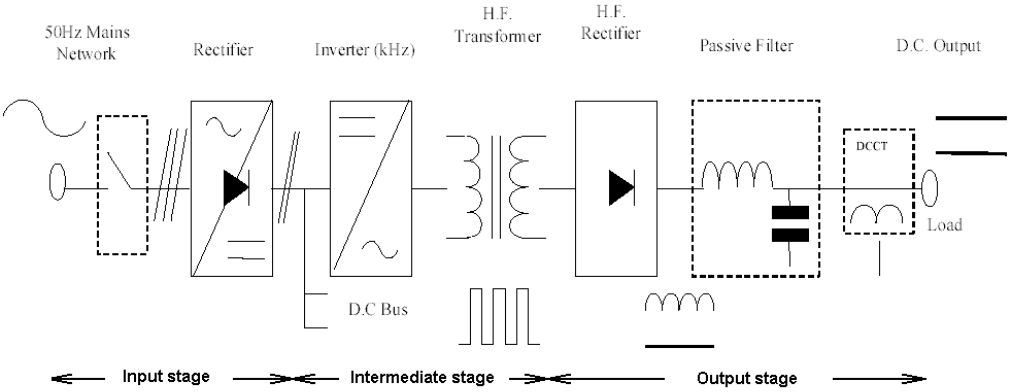

Figure 9.4: Basic structure of a switched-mode power converter.

A switched-mode power converter can normally be separated into three parts [3]:

1. Input stage – provides the interface to the mains as well as rectification of the input voltage.
2. Intermediate stage – performs high frequency switching and modulation of an AC voltage that drives the high frequency transformer.
3. Output stage – performs the rectification and filtering of the AC voltage and impedance matching to the load.

***Input Stage*:** There are a variety of input stages that could be considered. The easiest way would be a six-pulse diode rectifier connected to the mains and feeding all the units. An extension to this, which is more suitable for high power applications, is a 12-pulse diode rectifier, which is shown in Figure (9.5):

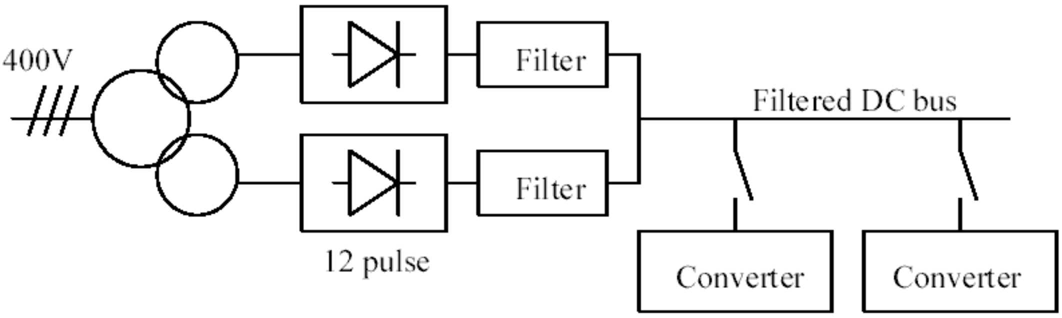

Figure 9.5: 12-pulse DC bus configuration.

Intermediate Stage**:** The DC bus voltage generated by the input stage maintains voltage to the high frequency switching unit. This unit converts the DC supply to an alternative source that drives the high-frequency transformer. Switching at high frequency reduces the size and cost of the components being used. The intermediate stage designs that are being considered here are the chopper and the full H-bridge.

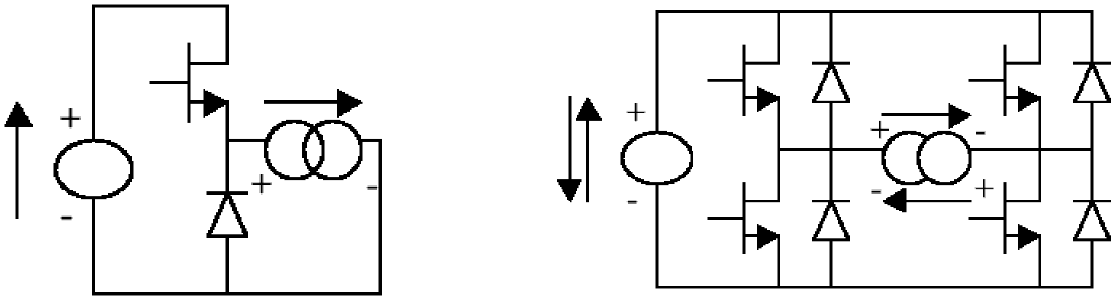

Figure 9.6 (a): Chopper. **(b): H-bridge.**

Output Stage: the output stage performs the rectification, filtering as well as impedance matching to the load. The size of the transformer and the output filter is inversely proportional to the frequency of operation. The size difference between the line transformer and the switch-mode transformer is approximately 20:1.

9.2.3.3.1 Chopped DC Regulator

The chopped DC regulator consists of a constant DC voltage produced by the input stage, which is connected to a fast switching element like an IGBT[1] or a MOSFET[2]. Choppers can be unipolar or bipolar depending on the configuration. The principle scheme of a unipolar chopper is shown in Figure (9.7):

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[1] - Insulated Gate Bipolar Transistor

[2] - Metal Oxide Semiconductor Field Effect Transistor

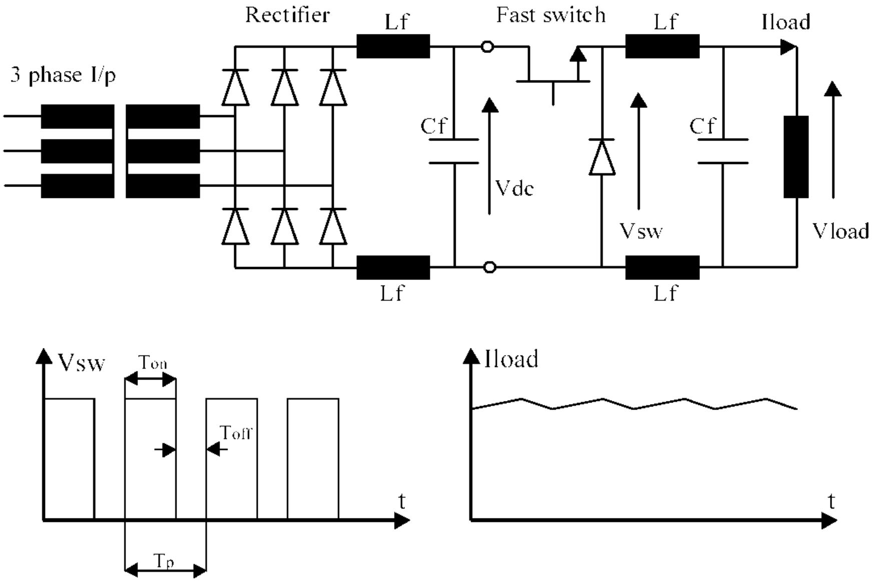

Figure 9.7: Configuration of a unipolar chopped DC regulator and the associated waveforms.

When the fast switch is conducting, the DC voltage appears on the LC output filter and the diode is blocked. When the transistor is off, the current through *Lf* finds its way through the diode and turns it on. The output voltage, which is equal to the average of the voltage on the output filter, is controlled by the width of the steering pulses. The output current has a biased rectangular shape, and its variation depends on the inductance and capacitance of the output filter. The switching frequency is limited by the switching losses and by the transistor turn-on and turn-off times and is normally *15-20kHz*. The bi-directional chopper works on the same principle but the fast switch is replaced by the H-bridge shown in Figure (9-6b).

The major disadvantage of a chopper is that the whole current has to be switched in each transition. This increases the noise emissions from the chopper and can cause mains disturbances. Besides, recovery charge of the fast diode increases the switch-on current of the transistor when the current is commutating out of the diode. This effect can cause intolerable strong emissions at medium/high frequencies (*0.1-5MHz*). The use of resonant converter, which is explained next can help removing these effects.

9.2.3.3.2 Resonant Converter

This design has the advantage of switching at zero current and therefore is not limited by the switching losses. With the resonant converter higher switching frequencies can be reached.

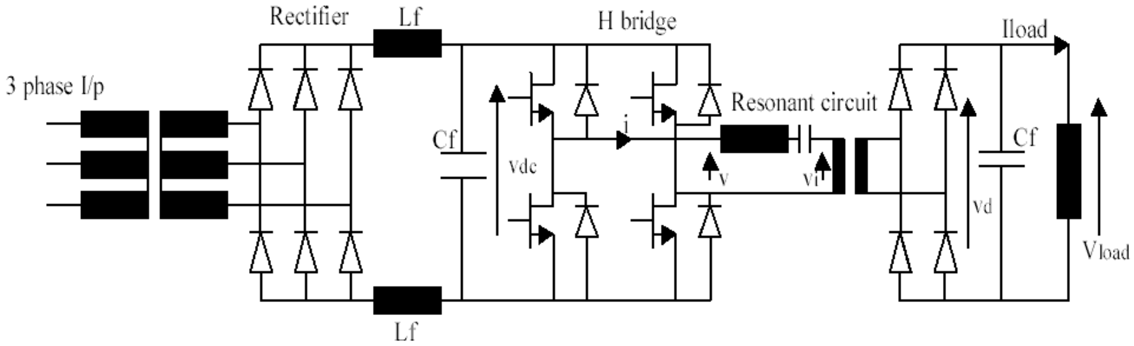

Figure 9.8: Principle scheme of a resonant power converter.

The configuration of a typical resonant converter is shown in Figure (9.8). The two branches of the H-bridge, which are switched alternately, create a rectangular voltage at the input of the transformer. The transformer current *i* which is nearly sinusoidal can have a leading or lagging phase difference with respect to the voltage *v* depending on the switching frequency. The secondary voltage of the transformer after being rectified, feeds the load. The capacitor *Cf* acts like a buffer and absorbs the current ripples.

The switching frequency of the resonant converter can be as high as a few hundreds of kHz without any switching loss problems. When the transistors are blocked, the capacitor in parallel with the transistors limits the *dU/dt* and significantly reduces the blocking losses.

Due to the absence of high harmonics, the losses in the conductors and ferrites are improved.

Switched-mode power converter issues can be summarized as follows [3]:

- Good power factor (0.95 approximately);
- For low power applications, small and light weight units could be built enabling fast replacement;
- High bandwidth due to high switching frequencies;
- Low output ripple and minimal size of output filtering;
- Well-proven technology with a variety of suppliers to choose from.

9.2.4 Power Converter Selection for SESAME

As shown in Table (9.2) there are a number of BESSY I power supplies, which can be used for SESAME and as well some power supplies which will possibly be available from SPEAR II. The final decision about the number and types of the new storage ring power supplies should be taken after a careful consideration of the existing power supplies and their conditions.

In the next paragraphs some remarks about the use of the different power converter technologies are presented for SESAME.

The linear power converter offers a low noise and small output ripple solution but because of its big size and poor efficiency which increases both running costs and the loading on the cooling system, it is considered unsuitable for a modern storage ring.

9.2.4.1 Dipole Power Converter

The two solutions, which are considered here for the dipoles, are the line-commutated and the switched-mode power converter.

The line-commutated thyristor power converter is a simple technology that is well understood with moderate purchase price and highest operational efficiency, which minimizes running costs and loading on the cooling system. For high power applications, the 12-pulse configuration can be used which minimizes the input supply harmonics and also reduces the size of the output filter. The power factor depends on the firing angle of the thyristors and in normal conditions a power factor of 75% is realistic. The power factor can be improved on demand by using additional circuitries. In order to decrease the ripples on the output voltage, an active filter may be necessary.

The switched-mode converter has a good efficiency but it's lower than the efficiency of line-commutated converters. This will increase the running costs and the load on the cooling system. The power factor is close to unity. The harmonics on the input supply can be minimized by careful consideration of the input filtering. It may require connecting several units in series or in parallel to provide the load with the needed voltage and current. This will increase the redundancy when *n+1* units are installed and will therefore decrease the downtime. Due to the high number of components, it will increase the system complexity and can have a negative effect on the system reliability.

9.2.4.2 Quadrupole and Sextupole Power Converters

The switched-mode power converter is considered the most suitable solution for the storage ring quadrupoles and sextupoles. There are different types of switched-mode power converter designs the manufacturer can choose from, considering the SESAME specifications.

The switched-mode power converter offers a compact, modular and lightweight solution, which minimizes the installation space and simplifies replaceability. The near unity power factor and the high efficiency are also its major benefits.

9.2.5 Pole Face Winding Power Supplies

According to the current design, there will be no separate defocusing quadrupole used in the storage ring. The defocusing function is accomplished using windings, which will be mounted on the poles faces of the dipole magnets. There are two strips on each of the pole faces of the dipoles. The two strips are rated at *100A/0.08V*. Although, in practice, one of the strips should have higher current compared to the other one (because of the non-uniform air gap of the dipoles). Number of the required pole face winding power supplies might be two or four depending on how the strips will be grouped (strips of the same type might be series-connected in one or two groups). Taking the total number of strips, drop on the cables and a good safety guard into consideration, the pole face winding power supplies should be rated at *120A/3V*. The stability requirement for these power supplies is the same as dipoles (i.e. 100ppm). There is no BESSY I power supply suitable for this application; therefore these power supplies should be new.

9.3 Booster Power Supplies

The magnets from the BESSY I booster will be used for the SESAME booster. The booster consists of 12 dipoles, 12 focusing and 6 defocusing quadrupoles, which form three families of magnets. All the magnets in each family will be connected in series and will be supplied by one ramping power supply. The power supplies are rated for 800MeV operation plus 10-15% safety guard for both current and voltage and as well for the cable drops. The reference currents of the three power supplies follow the ramping pattern, which is as follows:

1. The current stays at the injection level for some tens of milliseconds. In this period, the particles are injected from the microtron into the booster.

2. The current ramps up linearly to the extraction level in some hundreds of milliseconds as the particles are being accelerated.
3. It stays at the extraction level for some tens of milliseconds while the particles are injected into the storage ring.
4. The current decreases linearly to the injection level in some hundreds of milliseconds. During this period, the stored energy of the magnets is given back to the power supplies.

The whole process takes 1 second that corresponds to the 1Hz repetition frequency of the booster. The ramping intervals of Table (9.4) were considered for the calculations.

Table 9.4: Booster ramping intervals.

Booster	Time interval	Unit
Flat bottom	50	mSec
Positive ramp	450	mSec
Flat top	50	mSec
Negative ramp	450	mSec
Sum	**1000**	**mSec**

The current and voltage and the resultant active and reactive power waveforms of the Dipoles for one injection period are shown in Figure (9.9). The reactive power has been calculated for a B-6 configuration and would be smaller if a switched-mode power converter was considered.

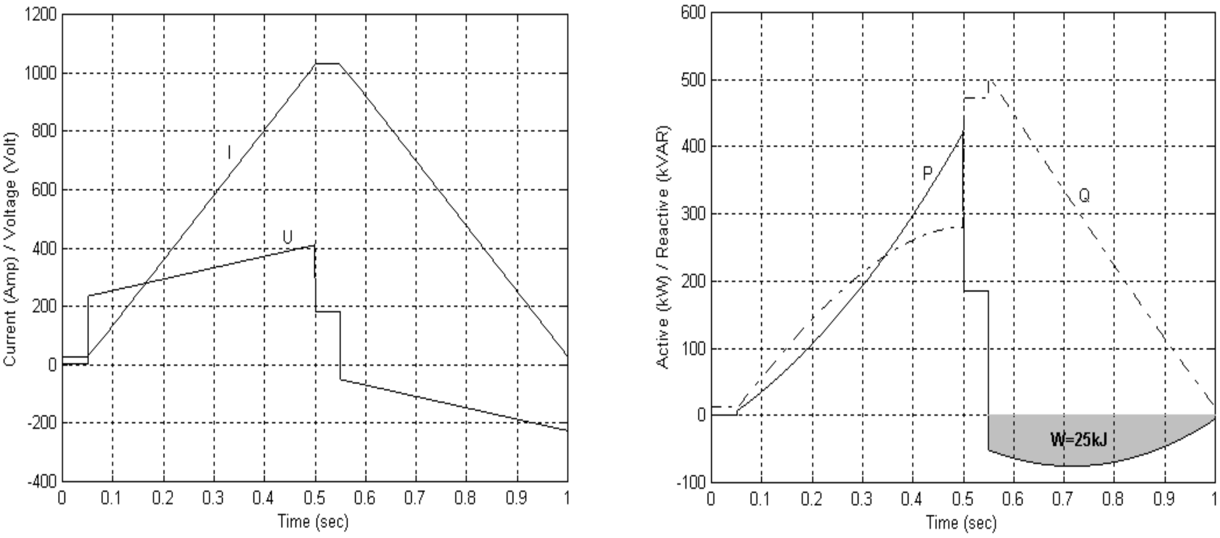

Figure 9.9: The left figure shows the current and voltage while the right one shows the active and reactive power waveforms of the booster dipoles. 12 diploes are connected in series. Total inductance=103 mH, Total resistance=175mOhm.

9.3.1 Discussion about the Waveforms

As can be seen in Figure (9.9), the voltage *U* consists of a resistive and an inductive part:

$$U = L\frac{di}{dt} + R.i \qquad (9.1)$$

In this equation, L is the inductance of the magnets, R is the internal resistance of the magnets and cables and i is the instantaneous current through the magnets. In the up-ramping period, both resistive and inductive parts are positive. In the down-ramping period the inductive part becomes negative while the resistive part is still positive. The resultant voltage during the down-ramping is negative which shows the need for a bipolar power supply.

The maximum active power occurs in the beginning of the flat top when both current and voltage are maximum while the maximum reactive power occurs in the moment when the current starts to decrease. During the down-ramping period, the active power becomes negative which means: return of the stored energy to the power supply. For the Dipole magnets, the stored energy is about 25kJ and with a repetition frequency of 1Hz this would mean 25kW of returning power. The following 2 alternatives have been discussed concerning the returned energy:

1. The returned energy could be given back to the mains. This alternative would result in less power consumption but some additional circuitry will be required to provide the return path for the current.
2. The returned energy could be dissipated in a resistor. Taking this alternative, the consumption of the electricity would be higher but the cost for the additional circuitry will be minimized.

The final decision should be taken considering the price of the electricity and the topology of the power supply being used. The second alternative, however, seems to be a better solution for SESAME.

Similar waveforms for the focusing quadrupoles are presented in Figures (9.10).

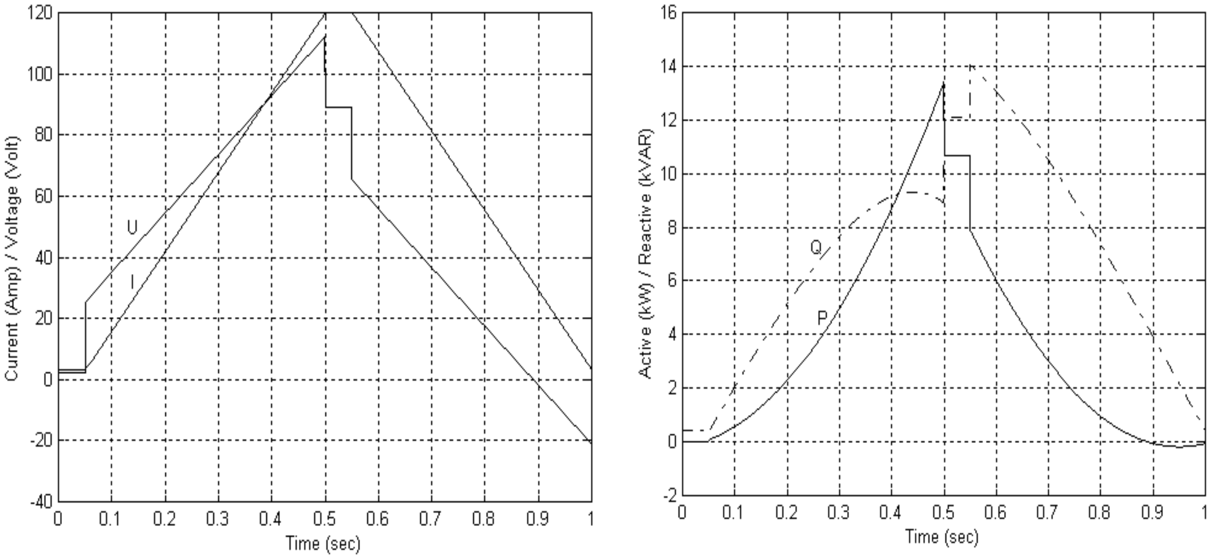

Figure 9.10: The left figure shows the current and voltage while the right one shows the active and reactive power waveforms of the booster focusing quadrupoles. 12 QF's are connected in series. Total inductance=89 mH, Total resistance=740mOhm.

For the 2 families of the quadrupoles, the returned power is negligible; no additional circuitry will be required.

9.3.2 Specifications of the Booster Power Supplies

The specifications of the booster magnets and power supplies are presented in Table (9.5). In order to provide a good safety guard, the nominal current and voltage of the power supplies are 10-15% higher than the optic requirements. The reactive and apparent power values have been calculated for a B-6 configuration without compensation. The reactive power would decrease if a switched-mode topology were used. Use of reactive power compensation circuits can also minimize the reactive power.

Table 9.5: Electrical specifications of the SESAME booster.

800 Mev	Dipole	QF	QD	Unit	Sum
Total inductance	103	89	45	mH	
Total resistance at 40 deg C	175	740	370	mOhm	
Time constant	0.6	0.12	0.12	Sec	
Number of circuits	1	1	1		
Num. of magnets per circuit	12	12	6		
Inductance per magnet	8.6	7.4	7.5	mH	
Resistance per magnet	14.6	61.7	61.7	mOhm	
Ext. current	1030	120	110	A	
Inj. current	20.6	2.4	2.2	A	
Maximum voltage	411.3	112.1	51.5	V	
Minimum voltage	-227.4	-21.5	-10	V	
Overall stability	100	100	100	ppm	
Max. active power	423.6	13.5	5.7	kW	442.8
Max. reactive power	500	14	6	kVAR	520
Max. apparent power	625	16	6.8	kVA	647.8
Power supply current	1200	150	130	A	
Power supply voltage	500	140	60	V	
Installed Power	600	21	7.8	kW	628.8
Transformer	756	26.5	9.8	kVA	792.3

Since the White circuits of the BESSY I booster could not be used for SESAME, the booster power supplies should all be new.

9.3.3 Dipole Magnet Power Supply

The preferred solution for the dipole magnet power supplies is a switched-mode power supply with a repetition frequency of 1Hz. A schematic diagram of such a power supply used at the SLS is shown in Figure (9.11). Similar schemes are also used / proposed for ANKA, ALS, DIAMOND, ELETTRA and CANDLE booster synchrotrons.

The scheme comprises two similar parts connected in series with a grounded mid-point. Each part is consisting of a delta/star transformer (for 30deg phase shifting), a diode rectifier, a one-quadrant DC chopper, a capacitor bank, two parallel-connected 2-quadrant choppers and the LC output filter. During the conduction mode, energy is transferred from the storage capacitor through the 2Q chopper to the load. The 1Q chopper is used to keep the level of the capacitors voltage constant. Control over the output voltage is accomplished by changing the duty cycle of the 2Q-chopper IGBTs. During the inversion mode, the current through the magnet finds its way through the diodes of the 2Q-choppers and charges the capacitor bank. The size of the storage capacitor should be big enough such that the variations on the capacitor voltage are not too high. As mentioned before, the preferred solution for SESAME is to dissipate the magnets stored energy in a resistor (in parallel to the storage capacitor). This would also decrease the size of the storage capacitor.

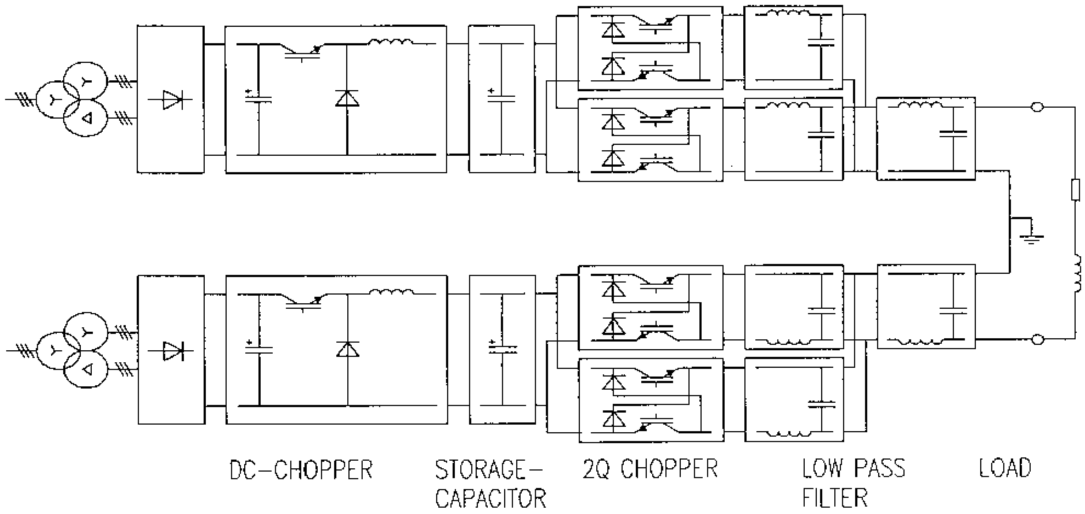

Figure 9.11: Principle scheme of the SESAME booster dipole power supply.

9.4 Correction Power Supplies

The total number of the storage ring correctors is 64, which include 32 horizontal, and 32 vertical magnets. The booster includes 12 correction power supplies. Each correction magnet is connected to a separate 4-quadrant correction power supply, which allows reversal of the current flow if necessary. The correction power supplies are small, modular DC-DC converters, which are normally of switched mode type and a number of them (ten to fifteen) are powered from a single unipolar DC source.

9.4.1 Correction Power Supplies of the Storage Ring

The specifications of the storage ring correction power supplies are summarized in Table (9.6).

Table 9.6: Correction power supplies of the SESAME storage ring.

2.5Gev	Corr – Hor	Corr - Ver	Unit
Inductance per magnet	2	0.700	H
Resistance per magnet	14	20.3	Ohm
Time constant	143	34	mS
Number of magnets	32	32	
Power supply current	1	2	A
Power supply voltage	16	50	V
Overall stability	100	100	ppm
Power	16	100	W

There are 36 correction power supplies available from BESSY I which are all rated at *10A/20V* with a stability of *1000ppm*. These power supplies are built in 1980 and cannot be used for SESAME because of the age and also because of their low stability. Therefore, the SESAME correction power supplies should be new.

9.4.2 Correction Power Supplies of the Booster

The specifications of the existing power supplies from the BESSY I booster are shown in Table (9.7).

Table 9.7: Correction power supplies of the BESSY I booster.

2.5Gev	Correction power supply	Unit
Number of power supplies	12	
Nominal current	1.5	A
Nominal voltage	30	V
Output power	45	W
Estimated input power	90	W
Overall stability	100	ppm
Manufacturer	GMS	
Type	Bipolar	
Year	1991	

These power supplies meet the requirements of the SESAME booster and they could be used for SESAME.

9.5 Power Supplies of the Transfer Lines

Each of the two transfer lines (microtron-booster and booster-storage ring) includes a number of quadrupoles and correction magnets, which are powered by separate DC power supplies. The specifications of these power supplies, which are existing from BESSY I are presented in Table (9.8).

Table 9.8: DC Power supplies of the BESSY I transfer lines.

PSs of the transfer lines	Microtron – Booster		Booster – Storage ring		Unit
	Corr.	Quads	Corr.	Quads	
Number of PSs	8	4	12	13	
Nominal current	1.5	20	20	50	A
Nominal voltage	30	70	25	20	V
Output power	45	1400	500	1000	W
Estimated input power	90	2800	1000	2000	W
Stability	100	1000	1000	100	ppm
Manufacturer	GMS	Delta	Foeldi	Hein	
Type	Bipolar	Unipolar	Unipolar	Unipolar	
Year	1991	1990	1980	1990	

The correction power supplies of the booster – storage ring have been built in 1980 and they cannot be used for SESAME. The rest of the power supplies may be used for SESAME depending on their conditions.

9.6 Disturbances to the Mains

The power variation of the booster synchrotron is about *600kVA*. These variations will be reflected on the low-voltage grid and in case they exceed the acceptable threshold, the ramping profile may be seen as flicker of the electric lamps. In the worst case it may result loss of the beam. The maximum disturbance that consumers are allowed to produce is defined in the grid specifications for each country. For example, this value is 3% in Germany according to the *VDE 0838* standard. For the range of flickering frequencies (up to *25 Hz*), this ratio is even lower. For SESAME, the allowed disturbance threshold at the machine site should be considered to be sure that the power variation of the machine is acceptable. If the variations were too high, *VAR*[1] compensation circuits should be used to decrease the voltage variation down to the allowed level so that it does not disturb other consumers.

9.7 Electronics of the Power Supplies

9.7.1 Introduction

Particle accelerators require magnet power supplies with very high performance. Important power supply considerations include reproducibility, stability and resolution. Typical values are *100 PPM*[2], *50 PPM*, and *16 bits*, respectively. Until recent developments, these requirements have always met through conventional analog electronics. Some modern accelerators like CERN (for the LHC project) and SLS have made major advances in this area as they are now offering a fully digital solution. In the following sections the basic structure and the operating principles of the digital and analog electronics are presented and their suitability for the SESAME power converters are investigated.

9.7.2 Conventional Analog Electronics

The basic structure of typical analog electronics is shown in Figure (9.12).

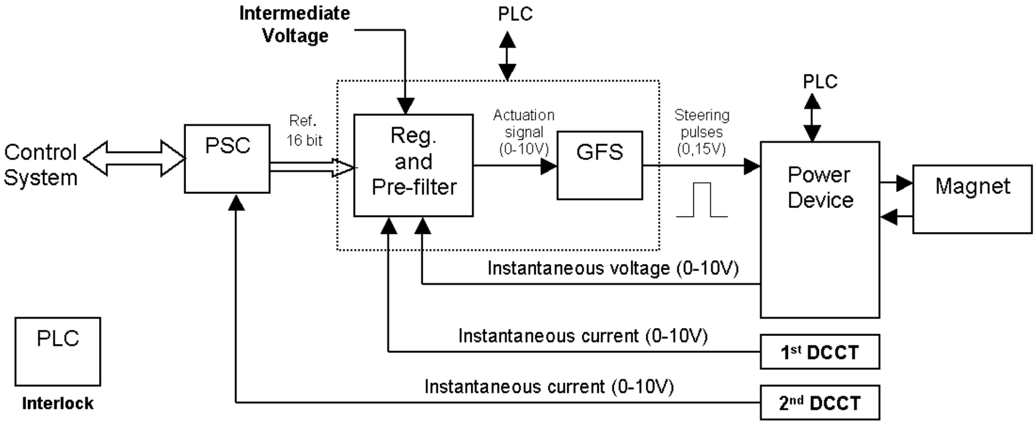

Figure 9.12: Basic structure of a typical analog system.

The *Power Supply Controller (PSC)*, incorporates an intelligent processor whose function is to provide the interface between the power converter and the control system. The processor translates the commands from the external control system and initiates the appropriate action such as representing the digital set current to the Regulation module or starting a current ramp. The *Reg. And Pre-filter* incorporates a DAC, which converts the digital set current to analog. The analog set current is compared to the actual current, measured by a DCCT to generate the current error, which drives the current and voltage PID regulators. The function of the *Pre-filter* is to compensate the ripples on the rectified input voltage (ex. when a chopper is supplied by a diode rectifier) by changing the width of the steering pulses. In this way the output voltage will be independent from the ripples on the DC input voltage. The *Gate Firing Set (GFS)* creates the amplified PWM (Pulse Width Modulation) signals according to the output of the Regulation. The 1st DCCT is a part of the current regulation loop while the 2nd DCCT is only used to monitor the current at the control room. In normal conditions, the two DCCTs show the samevalue. However, if there is a failure in one of the DCCTs, the two measured currents will

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[1] - Volt Ampere Reactive

[2] -Part Per Million

not be the same anymore. This can be used to quickly locate the failed DCCT between many power converters. Using only one DCCT for each power converter, it may not be easy to find the failed DCCT especially in big rings (ex. HERA ring).

The principle scheme of the current and voltage regulation loops is shown in Figure (9.13). The function of the current loop (the outer loop) is to regulate the current for long-term stability while the voltage loop (the inner loop) regulates the output for short-term stability. The voltage loop has a much higher bandwidth compared to the current loop; typical values are *1kHz* and *1Hz* respectively.

The precision of the output current depends mainly on the quality of the DAC. The output of the DAC can only be set to discrete values defined by the resolution. As a result the set current is always subjected to an error of up to +-0.5LSB[1]. Apart from this setting error, the precision of the output current is given by the analog errors of the DAC, the feedback loop and the quality of the DCCT.

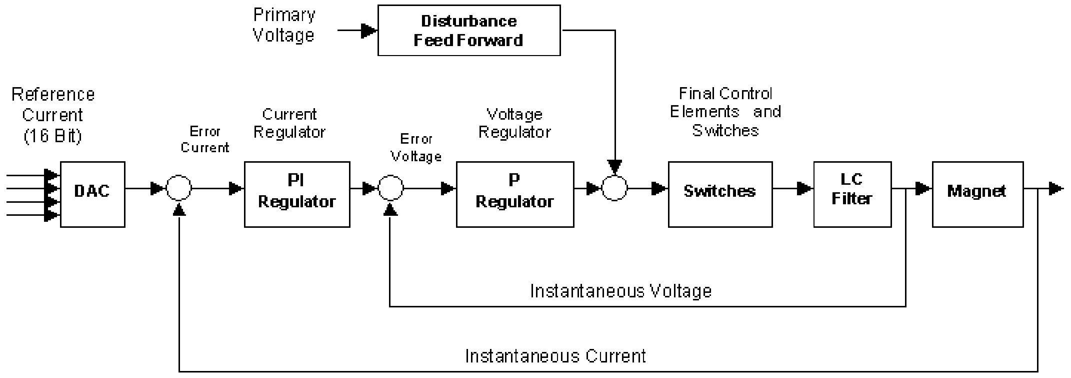

Figure 9.13: Principle scheme of the current and voltage regulation loops.

Noise is considered as one of the most important sources of error in an analog system. Analog circuits (ex. Op-amps) can malfunction when are subjected to noise. Apart from the environmental noise, noise can be generated by the following sources inside the power converter [3]:

- Mains frequencies (50Hz) and higher harmonics;
- Commutation of the power switches (IGBTs, MOSFETs);
- Auxiliary switching power supplies;
- Digital circuits, microprocessors, buses, etc;
- Spark generators such as relays, circuit breakers, etc.

Summary of the analog electronics:

- Proven technology that is well understood and extensively developed with a widely available competitive market;
- Uses PID regulators which require manual adjustment for optimization and commissioning;
- The stability of the output current is mainly dependent on the quality of the DAC and the DCCT;
- Any major changes in the control system will require a new design;

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[1] -Least Significant Bit

- Low level displays (LED type);

9.7.3 Modern Digital Electronics

A typical digital circuit is shown in Figure (9.14). In the digital system, the role of the intelligent processor becomes much more important as its functionality covers almost all of the building blocks explained earlier in the analog case. Since the reference current from the control system is already in digital, the need for the precise DAC is eliminated. This scheme however, needs a precise ADC to convert the measured current to digital before being fed into the processor. The precision of the output current now depends mainly on the quality of the ADC. The output voltage can be independent from the ripples on the diode rectifier voltage (intermediate voltage) by adding a dedicated ADC to the system, which measures the intermediate voltage. The resolution of the two voltage ADCs don't need to be high but their bandwidth need to be high to provide the required short-term stability (i.e. compensate for mains disturbances).

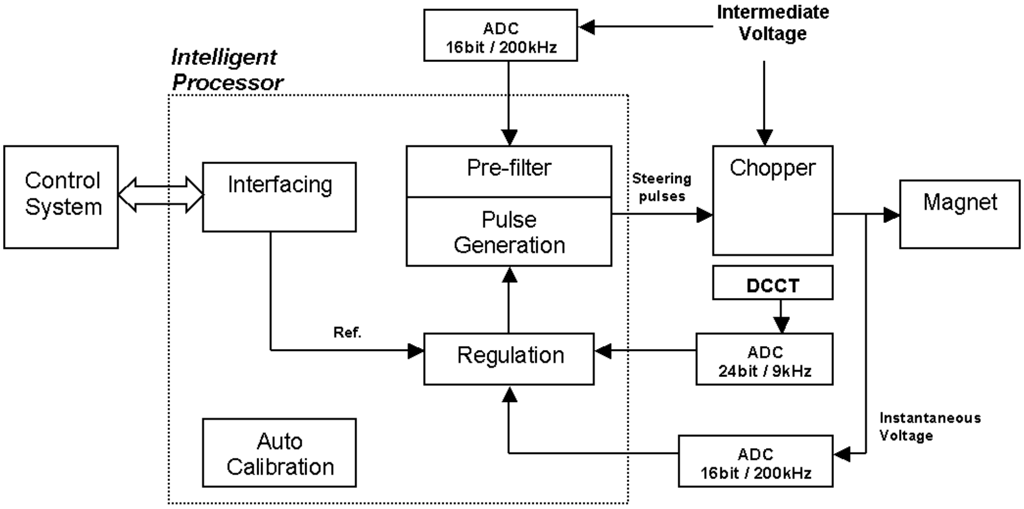

Figure 9.14: A typical digital electronic circuitry

Digital systems can also be affected by noise, although in general the levels are considerably higher than for analog circuits. Microprocessors can be particularly vulnerable to impulse noise.

Summary of the digital electronics:

- Still developing, but is the technology of the future;
- Limited commercial availability, low competition between companies;
- Allows software changes to optimize parameters during commissioning;
- Changes to the control system can be made in software, no redesign required;
- Can be connected to PCs, high quality monitoring;
- Extended functionality (ex. different shapes for the ramping curve, power supply data storage)
- Mainly based on the intelligent processor.

9.7.4 Recommendations for SESAME

The performance specification of the SESAME power converters can be achieved using analog or digital technology and the eventual decision should be made at the tender evaluation stage after all the proposals have carefully been considered. However, in general using a digital system is preferred because of the advantages associated with it.

9.8 Magnet Cables

This section focuses on the issues relating to the dipole, quadrupole and sextupole magnet cables and the associated voltage drops due to the cable resistance and the current flowing. The CSA[1] of the cables are chosen with respect to the flowing current, air temperature and the cable configurations. Flow of current around the booster and storage ring generates undesirable vertical magnetic fields that may cause malfunction of other devices if not compensated. Therefore, the cables should be installed in such a way that currents moves in both clockwise and counterclockwise directions around the ring. This will result zero vertical magnetic field.

9.8.1 Cable Conductors and Sizes

The two conductors that are considered here are Aluminum and Copper. Generally, Aluminum is lighter and cheaper but it can withstand lower current densities. The main disadvantage of Aluminum is its low flexibility, which limits its use for the SESAME booster and storage ring magnets. Nevertheless, Aluminum can be a good choice when long straight cables should be installed. Copper cable is considered the most suitable solution for the booster and storage ring magnets.

According to the cable data, a single-core Copper cable with CSA=185mm^2 can be used for current values up to 405A at 25deg C. Therefore; it can be used for the storage ring quadrupoles. For higher currents (ex. dipole magnet cables) it's preferred to put two or more 185mm^2 cables in parallel rather than using one cable with higher CSA. For the storage ring sextupoles and booster quadrupoles, cables with CSA=95mm^2 are suggested which can be used for currents up to 265A at 25deg C.

9.8.2 Cable Losses

Table (9.9) shows results of calculations for the power losses and voltage drops on the cables.

Table 9.9: Cable power loss calculations.

	Storage ring			Booster			Unit
	Dipoles	**Quads**	**Sexts**	**Dipoles**	**QF**	**QD**	
No of families	1	2	4	1	1	1	
Cable length / family	260	260	140	85	85	85	m
Cable CSA	185*2	185	95	185*3	95	95	mm^2
Conductor	Copper	Copper	Copper	Copper	Copper	Copper	
Current capacity at 25C	810	405	265	1215	265	265	A
Unit resistance	48.2	96.4	188	32.1	188	188	uOhm / m
Total resistance	12.5	25.1	26.3	2.7	16	16	mOhm
Maximum current	643	356	140	1030	120	110	A
Power supply voltage	700	120	100	500	140	60	V
Voltage drop	8	8.9	3.7	2.8	1.9	1.8	V
Drop in % of supply voltage	1.1	7.4	3.7	0.6	1.4	3	%
Power loss per family	5.1	3.2	0.5	2.9	0.2	0.2	kW
Total power loss	5.1	6.4	2	2.9	0.2	0.2	kW

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[1] - Cross Section Area

9.8.3 Connection of the Magnets

The magnets should be connected in such a way that the total vertical filed is zero. Three configurations were considered concerning connection of the magnets to the power supplies. These are shown in figures (9.15a)-(9.15c):

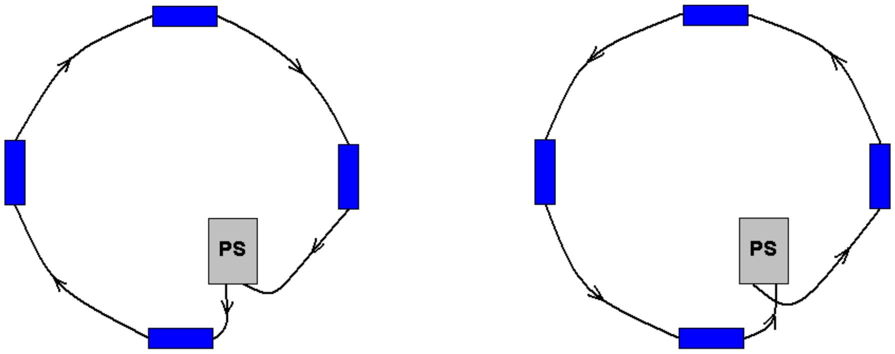

Figure 9.15 (a): Vertical field compensated in two circuits, Cabling=circumference

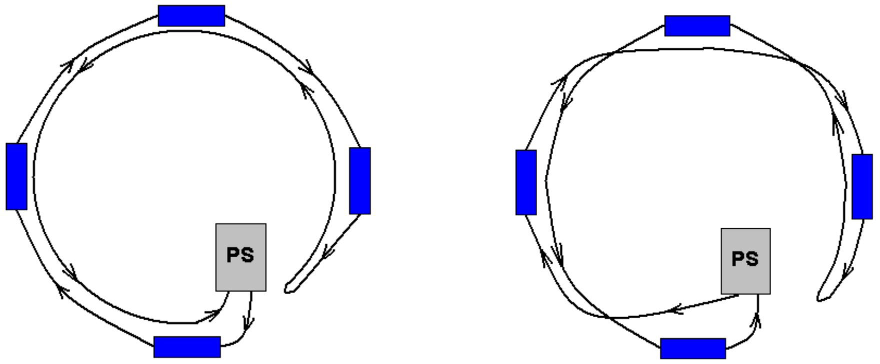

Figure 9.15 (b) **Figure 9.15 (c)**

Vertical field compensated in one circuit, cabling=2*circumference

Configuration (a) allows minimum amount of cabling which is roughly equal to the circumference of the ring. However, this configuration can only be used when there are two loops with the same current value. The current in the second loop moves in the opposite direction of the first loop, therefore the total magnetic field is zero. Configuration (a) can be used for the four families of the storage ring sextupoles.

When configuration (a) is not possible, either of the configurations (b) or (c) may be used. In both cases cabling is two times the circumference but in configuration (c) cables with equal lengths are used that simplifies the installation of the cables. Configuration (b) needs a long cable running around the whole ring, which may not be easy to install. For this reason, configuration (c) is preferred compared to (b) for SESAME.

In all the three configurations, both cables should be located close to each other such that there will be no leakage flux passing between them.

Connections of the SESAME magnets have been summarized in Figure (9.16a) and (9.16b). For the four families of the sextupoles, configuration (a) is used. For the rest of the magnet families, configuration (c) is used.

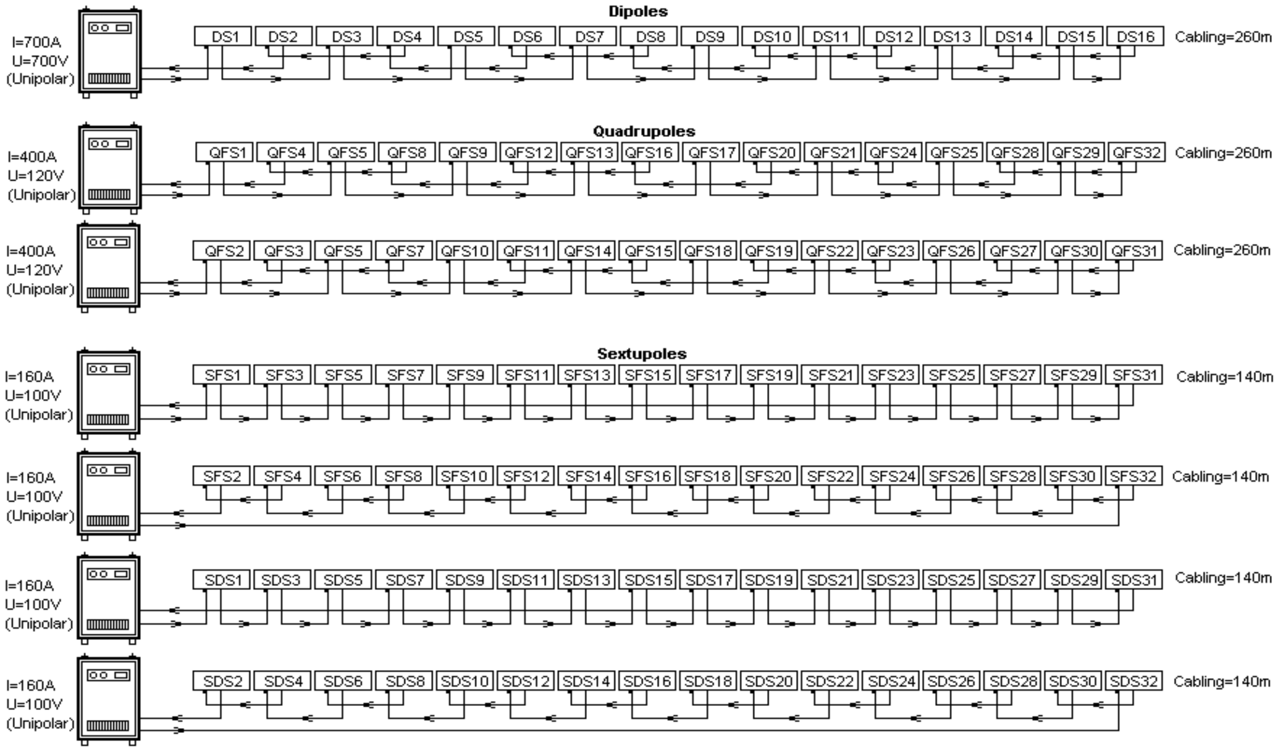

Figure 9.16a: Connection of the storage ring magnets; for the dipoles and quadrupoles, vertical field is compensated in one circuit; for the sextupoles, field is compensated in two circuits.

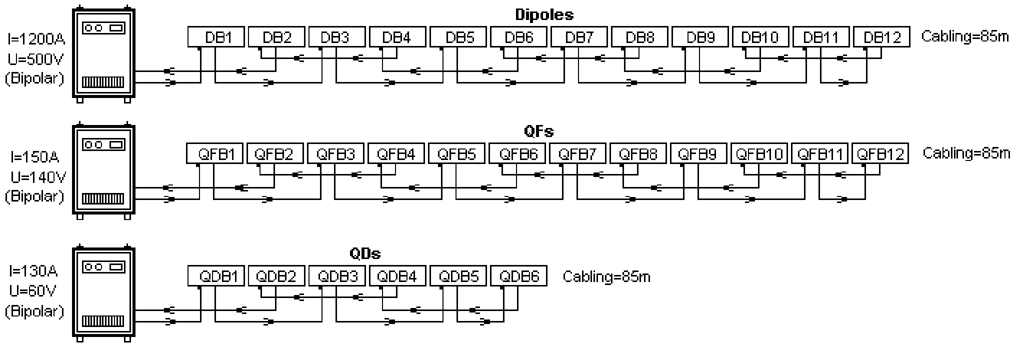

Figure 9.16b: Connection of the booster magnets; vertical field is compensated in one circuit for all the families

9.8.4 Cable Trays

A schematic view of the SESAME cable trays is shown in Figure (9.17). Cable trays will be installed inside the ring close to the girder system. The first estimations revealed that three trays each with a width of 30cm are enough for the installation of the booster and storage ring magnet cables and the communication cables. The widths of the cable trays may be decreased to 15-20cm to simplify working on the magnets from inside the ring but then, more trays will be needed. On both sides of the girders, there are enough spaces for the operator to work on the magnets and the other components. The transformer cables and the water-cooling pipes are installed in the double-floor section that covers the area between the two shielding walls as shown in Figure (9.17).

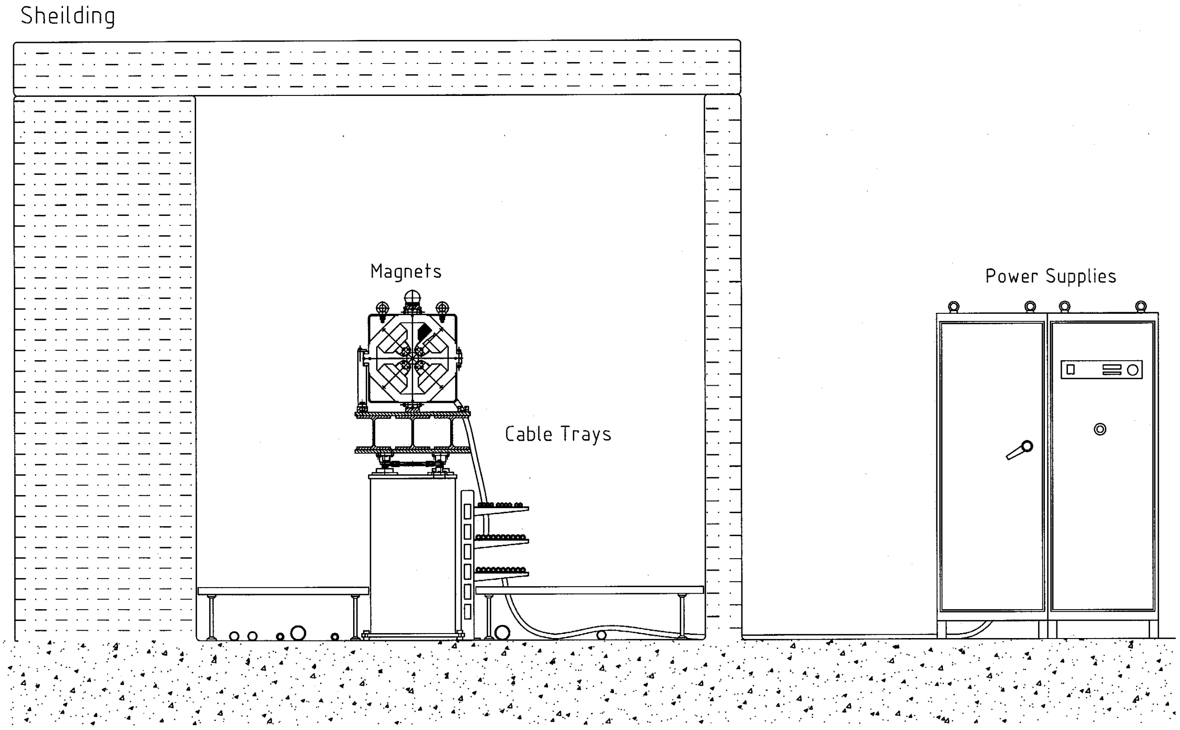

Figure 9.17: Schematic view of the cable trays inside the tunnel.

9.9 Location of the Power Supplies

The top view of the SESAME ring placed inside the shielding wall and the locations of the power supplies are shown in Figure (9.18). The area inside the ring will be used for the installation of the booster and storage ring power supplies and the distribution boards. As shown in the figure, there's a bridge / staircase connecting the first floor of the building to the inner side of the ring on the ground floor. The bridge carries the mains cables coming from outside of the main building. In order to minimize the lengths of the magnet cables, the storage ring power supplies and distribution boards will be installed near to the bridge. The booster power supplies will be located around the booster synchrotron but out of the shielding wall. The MV/LV[1] transformers will be installed out of the main building. The power switches and the circuit breakers will be installed in the technical building, which is separate from the main building.

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[1] - Medium Voltage / Low Voltage

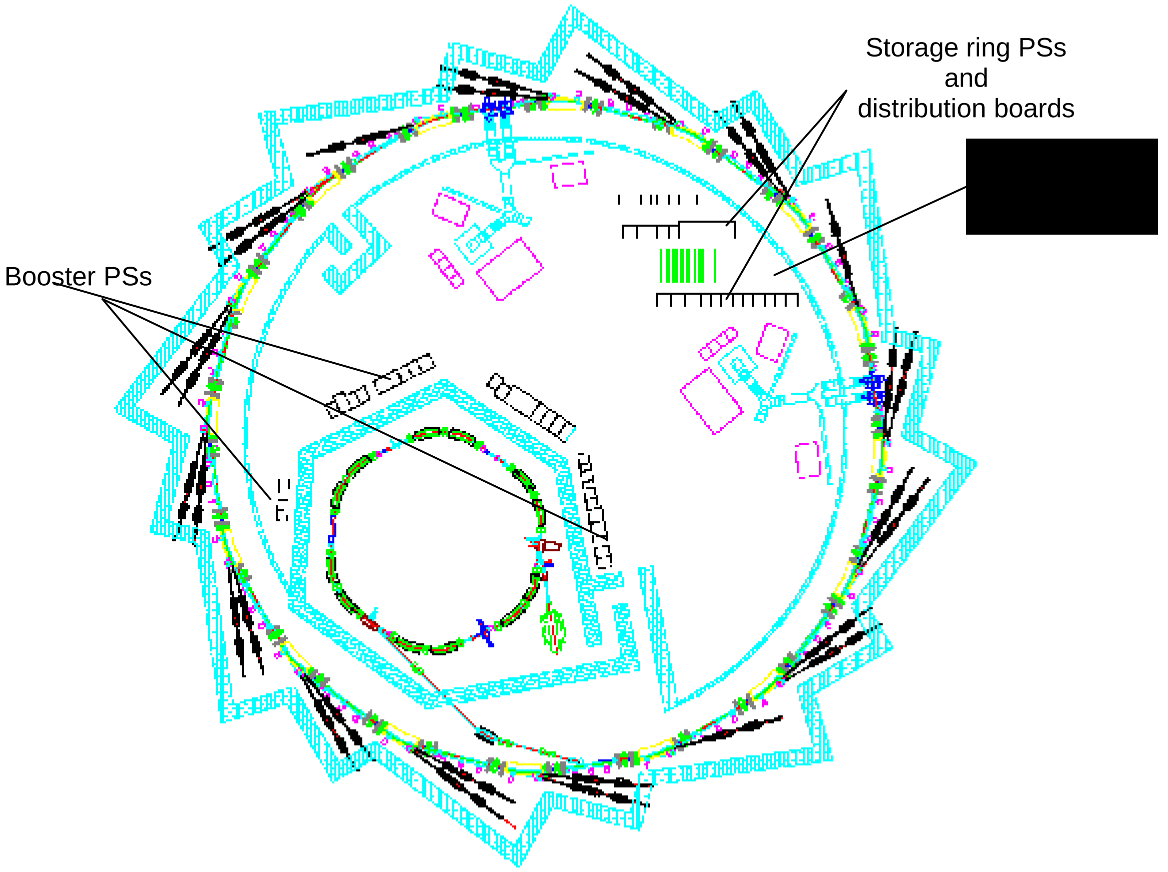

Figure 9.18: Location of the power supplies inside the ring.

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[2] D. Einfeld, "SESAME 2.5GeV ", Jan. 2003.

[3] Diamond concept report, draft1.

[4] Concept design for the Candle project, July 2002.