AN OVERVIEW OF THE LEP POWER CONVERTER SYSTEM

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This paper describes the power converters of the LEP Main Ring which feed the entire magnet system, the RF klystrons and the vacuum pumps with dc power. The output power range varies from a fraction of a kW to several MW. The highest voltage is 100 kV and the maximum current 33 kA. The principles described lead to a design which is extendable from LEP Phase 1 (65 GeV) up to 100 GeV beam energy. Low initial investment is as important as high reliability and minimum operational cost, not forgetting the demand of continuous performance improvement. Under worst case environmental conditions, the best specified current stability is $\pm$ 5.10^{-5} of the maximum current over four hours. The current range for unipolar converters is 100:1. That of bipolar converters for correction magnets is extended to 1000:1 thus permitting a smooth passage through zero.

General Design Considerations

The best conversion efficiency consistent with overall design simplicity is required in order to achieve a low purchase price, good reliability, and reasonable operating costs. Special attention is paid to reduce electromagnetic interference, and in particular mains voltage disturbances caused by 50 Hz harmonics. For economic reasons no active redundancy can be considered.

All converters, except the main dipole converters and the 33 kA converter for the LEP L3 physics experiment, will be air-cooled, thus minimizing ancillary cooling equipment and its associated supervision. The high-power transformers and diode rectifiers are oil-immersed using natural oil-convection, and the tanks, naturally air-cooled, will be located outdoors.

Every effort is made to use the same electronic control modules for each type of converter. These modules are designed for fully automated testing and are being built using high-quality components to enhance reliability. All electronics modules will undergo a burn-in period to reduce initial failures.

The Converters for The Magnet System

General

Table 1 is a summary list of the power converters for the magnet system, their dc output characteristics, performance and current range. Special attention was paid to circuit configurations which allow current ranges of up to 100:1 for unipolar converters and 1000:1 for bipolar ones. The dc current stability includes the effects due to load drifts and temperature variations from 20°C to 30°C as well as normal mains fluctuations. The most stringent requirement for the 4-hour current stability is $\pm$ 5.10^{-5} and $\pm$ 2.10^{-4} for the current reproducibility over one week.

All unipolar power converters of up to 37 kW dc output power and all the four-quadrant dc converters below 1 kW are of the switch-mode design. For the LEP Main Ring magnet system, this represents more than 80% of the number of converters which are constructed in this new technology totalling about 50% of the system cost.

Magnet circuits	Number of converters	Characteristics			Current Range	Current stability
		I (A)	V (V)	P (kW)	Imax/Imin	ΔI/Imax 4 hours
Main dipoles	1	2900	2400	6960	3 : 1	±5.10^{-5}
Dipoles in injection regions	1	340	750	255	"	"
Quadrupole QF	2	275	2600	715	5 : 1	±5.10^{-5}
Quadrupole QD	2	275	2600	715	"	"
Compensation	1	± 50	± 250	12	100 : 1	±1.10^{-2}
Sextupole SF	4	110	130	14	17 : 1	±1.10^{-4}
	8	110	250	27	"	"
Sextupole SD	4	130	160	21	"	"
	8	130	320	42	"	"
Quadrupole QSC	8	2000	10	20	4 : 1	±1.10^{-4}
Quadrupole QS1	8	300	200	60	"	"
Quadrupole QS2	8	485	95	46	"	"
Quadrupole QS4	4	260	175	45	6 : 1	±2.10^{-4}
Quadrupole QS5	8	190	70	13	"	"
Quadrupole QS6	4	260	180	47	"	"
Quadrupoles QS17,18	8	140	120	17	"	"
Quadrupoles QS7/9	4	200	265	53	"	"
Quadrupoles QS8/10	4	200	265	53	"	"
Quadrupoles QS3, 11-16	28	190	150	28	"	"
Quadrupole QL1	4	300	450	135	4 : 1	±1.10^{-4}
Quadrupole QL2	4	485	250	120	"	"
Quadrupole QL4	4	260	230	60	6 : 1	±2.10^{-4}
Quadrupoles QL17,18	8	140	145	20	"	"
Quadrupoles QL7/9	4	200	305	61	"	"
Quadrupoles QL8/10	4	200	305	61	"	"
Quadrupoles QL3,5,6 11-16	36	190	180	34	"	"
Mini wigglers	4	55	200	11	3 : 1	±1.10^{-3}
Titled quadrupoles	24	± 55	± 70	4	100 : 1	±2.10^{-4}
Wigglers	2	550	350	192	"	"
Wigglers trimming	4	± 5	± 135	0.7	"	"
Correctors CH, CV	520	± 5	± 135	0.7	1000:1	±5.10^{-4}
Correctors CHB, CVB	24	± 55	± 70	4	"	"

Table 1 - Magnet Power Converters for LEP Phase 1 (65 GeV) Summary List

Converters for the main bending magnets and the quadrupole chains

The two recuperated ISR Main Ring power converters will be used to feed the chain of LEP Main Ring bending magnets. Figure 1 shows a schematic of the general arrangement of the converter. Under normal operating conditions, only one quarter of the total dc system voltage is applied between any point of the magnet windings and earth.

The rectifier transformers are fed from the LEP three-phase 18 kV mains supply which takes its power from the 400 kV EdF (Electricité de France) grid.

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The winding arrangement of the transformers is such that they form a 24-pulse system. This eases dc filtering and considerably reduces the fifth, seventh, eleventh and thirteenth harmonic distortion of the main distribution system. Computer simulations have shown that great care has to be taken to ensure symmetrical excitation of the magnet chain during acceleration in order to avoid delay-line-type oscillations. One of the measures necessary is to arrange the power converters in a symmetrical way with respect to earth. This not only concerns the rectifiers themselves, but also the passive filter arrangements.

The two transformer tanks, each containing two transformers, will be located on pits outside the Equipment Building; the rectifier and passive filter cubicles will be housed inside the building. For the complete converter to be current-stabilized, the master will be current-controlled whilst the slave unit will be voltage-controlled.

Each of the two quadrupole chains is fed by two power converters, in a similar way to that used for the main bending magnet. Each converter is built up of two modules which deliver positive and negative output voltages that are symmetrical to earth potential. The thyristor rectifier will be fed from 18 kV outdoor oil-filled transformers. The 12-pulse thyristor blocks and passive filters will be housed indoors, with feedback, control, interlock and electronics in adjacent cubicles.

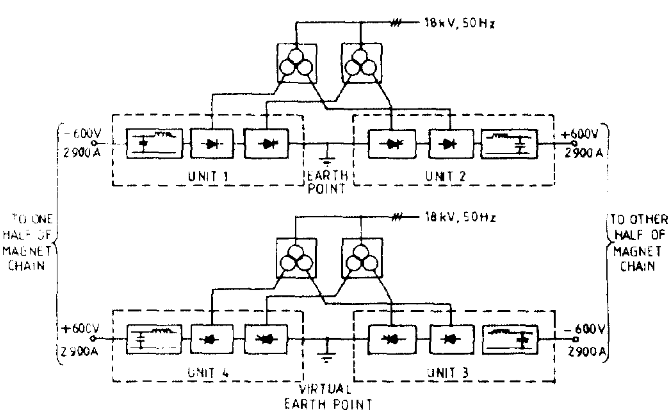

Fig. 1 - Power converter for main ring bending magnets

Converters for individual magnet loads

The "individual magnet loads" consist of a small number of magnets of the same type connected in series. More than two hundred such strings have to be powered. Their ratings vary from a few kW up to 250 kW. A considerable design effort was invested to find an economical solution such that all the hardware which will be purchased for LEP Phase 1 can be re-used for LEP beam energies as high as 100 GeV.

In the power range up to 37 kW a modular system was chosen. Switch-mode converters, based on a resonant circuit, achieve compactness as well as high efficiency. Different transformer connections will adapt the output dc currents and voltages within a range of 2:1 (300 A, 125 V to 150 A, 250 V). The conception of these modules allows them to be connected in parallel. Details of the designs are presented to this Conference in another paper.

The converters for the superconducting quadrupoles (2'000 A, 10 V) will be housed at the bottom of the vertical access shafts. A compact and low-loss unit is achieved by switch-mode technology.

The power range above 37 kW is covered by converters in the traditional 50 Hz line commutated thyristor technology with a three-phase isolation/adaptation transformer. For the needs after LEP Phase 1, wherever this was necessary, a 12-pulse power circuit with a split L-C filter was chosen which facilitates change-over from parallel-to-series connections and vice-versa.

For magnets requiring bipolar excitation in the presence of a beam, four-quadrant converters will be used. Units consisting of antiparallel thyristor bridges with a circulating current (known as dual converters) fulfil this role.

Converters for Correction Magnets

520 converters are required for feeding the individual correction magnets. The need for a smooth control of the current through zero dictates the use of a bipolar converter. Mechanical polarity switches would create both timing and reliability problems, and therefore a purely electronic solution was chosen. This aim is achieved by a novel 135 V, 5 A, switched-mode bipolar converter. It uses a primary rectifier-inverter stage connected directly to the three-phase 380 V mains. The H-type output stage permits a four-quadrant bipolar operation over an extended current range. All high-voltage semiconductors are POWER MOSFETS.

Power converter for the magnet for LEP L3-Physics Experiment

The magnet located underground will be fed by 33'000 A, 170 V dc. The converter, situated at the surface, consists of two oil-immersed converter transformers which feed six water-cooled thyristor modules. The dc filtering is achieved by six L-C filters connected in parallel to the bus bar system.

High-Voltage Power Converters for RF Klystrons

For LEP Phase 1, eight high-voltage converters will be installed. Each converter has an output rating of 100 kV and 40 A, and feeds two klystrons. The converters are totally shielded thus removing the need for a high-voltage substation. The design takes into account the special operational requirements which stem from using klystrons as a load. The klystron protection system, known as the crowbar, operates by short-circuiting the output terminals of the converter. This requires careful design and protection methods, and mechanical as well as electrical fatigue problems had to be considered.

Each power converter consists of four units (Figure 2) :

- the step-down transformers (TR1 and TR2)
- the thyristor ac regulator and its electronics
- the high-voltage transformers (TR3, TR4)
- the diode-rectifier and filter-choke unit.

The primaries of the two step-down transformers are fed from the 18 kV, 50 Hz, three-phase mains.

The 1 kV secondary output voltages form two three-phase systems which are shifted in phase by 30° (electrical) in order to obtain a twelve-pulse system at the dc output terminals. The 30° phase-shift is attributed symmetrically to the two step-down transformers (±15°).

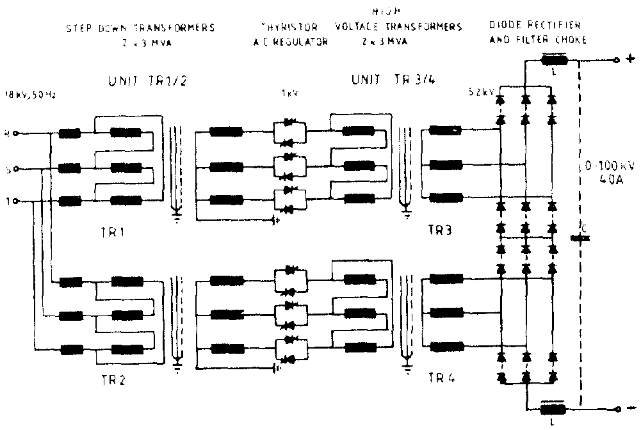

Fig. 2 - Electrical circuit of a thyristor controlled dc power converter rated at 100 kV, 40 A

The ac thyristor regulators are connected between the secondaries of the step-down transformers and the primaries of the high-voltage transformers. The thyristors are connected in an antiparallel configuration. The choice of 1 kV as the value of the intermediate voltage level allows the use of high-power thyristors without connecting devices in series. The current in the ac controller is handled by two parallel thyristors in each branch. Together with the electronics cubicle, the ac regulator forms a compact unit located inside Equipment buildings. The thyristors are capable of repeatedly switching off the converter under short-circuit conditions without long-term degradation of their characteristics.

The high-voltage transformers step up the voltage from 1 kV to 52 kV. Their output terminals are connected to high-voltage diode bridge rectifiers. Each bridge arm consists of series-connected diodes mounted on cooling fins, and of voltage equalizing resistors and capacitors. The two diode bridges are placed in series and are connected via two 2.5 H filter chokes to the output terminals.

All high-voltage components, i.e. the step-down transformers, the high-voltage transformers, the diode bridges and the filter chokes, are immersed in mineral oil and housed in three separate tanks.

The high-voltage transformer tank is connected through separated oil-filled ducts to the tank containing the diode bridges, the chokes, and the precision high-voltage dividers. In this way, the optimum oil temperature can be used for each element, thus obtaining an economic and reliable system. The output power is fed through two shielded high-voltage dc cables to the klystrons in the klystron gallery.

The dc cables are connected, inside the rectifier-filter oil tank, to the high-voltage terminals via an easily dismountable feedthrough arrangement.

High-voltage Power Converters for Sputter-Ion Pumps

A total of 580 high-voltage dc power converters are needed to supply the ion pumps of the vacuum chambers in the machine arcs and the RF sections. The chosen design consists of a leakage transformer equipped with a magnetic shunt and a voltage-doubler. The power converter is able to run under short-circuit conditions without damage.

The main electrical characteristics are : open-circuit voltage, 5.8 kV; short-circuit current, 225 mA; maximum output power of 250 W (at~40% of open-circuit voltage).

Control Electronics

Each power converter will be equipped with control electronics, where the functions of regulation, protection and remote control are integrated into one unit. This approach substantially reduces the overall construction costs and also provides improved protection against electrical interference.

The regulation electronics is based on conventional analog methods. This approach gives the most cost-effective solution where high performance is required. However, some closed-loop digital correction may be applied internally to correct for long-term drift of critical components.

In each power converter a master microprocessor co-ordinates all internal and external actions, whilst a second slave microprocessor controls the ramping of the digital-to-analog converter (DAC), which provides the current reference. The corresponding output current is measured by a multi-slope analog-to-digital converter (ADC).

The control electronics are designed and constructed in a highly modular form, where major functions are contained on individual printed-circuit boards. The majority of power converters employ the same boards, thus reducing both the construction and testing problems and keeping spares inventories to a minimum. The whole electronics is based upon the EUROPE chassis and card system.

Acknowledgements

Our thanks go to the members of the LEP Power Converter Group for their responsibility for the conception and the design, and to industry for the realisation of the LEP Power Converter System.

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