

# REALIZATION OF THE LEP POWER CONVERTERS

H.W. Isch

European Organization for Nuclear Research  
CERN, CH-1211 Geneva 23, Switzerland

## Abstract

After a phase of intensive and detailed preparation, which included preliminary inquiries to a wide variety of firms, more than forty contracts and large orders were placed with industry. They cover the power part of the converters for the magnet system, the RF klystrons and the vacuum pumps as well as the electronics for the supervision, control and local intelligence for these high-precision equipments.

The first deliveries of the series production started in the second half of 1986 and by the end of 1987 most of the high-power units for the magnet system have been delivered to CERN. After thorough tests they are being installed in the LEP equipment buildings. This includes all the equipment necessary for the injection tests into LEP octant 1 to 2, scheduled for July '88.

The tests on the prototype 100 kV, 40 A converter for the RF klystrons were successfully terminated with a full power run on the RF test string. The first sets of the series units are being delivered, tested and installed.

An important aspect for obtaining high reliability lies in the automatic test procedures which are rigorously carried out, starting at the module level and ending at the complete equipment.

## Introduction

The realization of the LEP power converters started late in the LEP project. This was mainly due to the constraints of the LEP budget profile. As the LEP expenditure had to be paid within the constant CERN budget, any peak of expenditure had to be avoided. One of the consequences was to order the LEP power converters as late as possible. This meant a very careful preparation of the whole operation in order to prevent problems resulting in delays in the procurement of these vital LEP components.

Our aim was to build reliable power converters, compatible with the latest achievements in technology. They would not only be used in LEP phase 1 but had to be adaptable for running LEP up to 100 GeV. At the same time we continued the effort to beat inflation, in Swiss francs, as we have done over the past two decades. The preparation work was divided into two phases which partially overlapped. The first one consisted of development work in our laboratory, exploring new ideas on advanced technologies in the fast moving field of power converters. The second was to consult the electrical industry of the CERN Member States. To this end, preliminary inquiries on power converters for the LEP magnet system were sent to more than 400 firms.

## Preliminary inquiries

These inquiries served as advanced information to European industry and at the same time as a market survey in the field of power converters in general and the advanced field of power electronics in

particular. They gave a general description of the LEP project, a short technical specification with a technical/commercial questionnaire and a list of qualifying criteria. They were neither calls for tenders nor did they ask for budget prices. Nevertheless, firms who did not reply were not invited for the final calls for tenders.

For the converters of the LEP main ring magnet system, the preliminary inquiry was subdivided into eight chapters resulting later in eight technical specifications. Each chapter covered in general one type of technology. The choice based on output power, d.c. current, etc. was such that a large number of manufacturers would be interested in every call for tenders. We had constantly to keep in mind that not only our material budget was very limited but also the number of CERN staff could not be increased. A careful balance had to be found in the definition of the work extent, especially on how much on-site work was included. Experience had shown that competition among a large number of competent suppliers is the best way to get good value for money.

The commercial questionnaire was established to ascertain that manufacturers had sound financial basis to handle such contracts and that they had the potential to serve other customers as well when handling a large CERN contract. The first part of the technical questionnaire concerned the firm's development, manufacturing and test facilities, number of qualified staff and their field of experience. The second part had specific questions on technology proposed, to solve in the most cost effective manner given problems, quoting the boundary conditions such as space and efficiency.

Due to lack of time and manpower, it was not possible to visit firms which had replied to the preliminary inquiries nor to discuss with them in detail their replies.

## Call for tenders

After a careful analysis of the answers to the preliminary inquiries, the final technical specifications were written and the lists of potential suppliers established. This work started in 1985 and its bulk, consisting of more than thirty calls for tenders, was finished within twelve months.

After tender opening, the manufacturers offering the lowest price were systematically visited in order to check that they fulfilled the qualification criteria and to ascertain that they had fully understood the specification. Questions on reliability and quality assurance were discussed as well. Finally, the production and test facilities were inspected.

In two cases the series production was preceded by qualification prototypes. CERN ordered first from the lowest bidders qualification prototypes. After successful completion of these units, the series was to be ordered from the manufacturer offering the lowest overall bid.

### The power converters for the magnet system

The two ex-ISR main power converters will feed the LEP bending magnet chain with d.c. power. A major reliability improvement and adaptation program was carried out in house on the rectifier transformers as well as on the diode/thyristor units. In order to have a symmetrical arrangement with respect to earth for the two magnet halves, two choke capacitor filter units had to be added. The filter capacitors could be found on site, therefore only two chokes had to be purchased from industry. The installation and interconnection of these units started late 1987 and is carried out by contract labour.

The converters for the two long chains of quadrupoles and for the injection dipoles are of a very similar design and power level. One of the specifications dealt with the oil-immersed rectifier transformers, five in total, connected on their primaries to the 18 kV mains network and having multiple sets of secondary windings. The second specification covered the thyristor and passive choke-capacitor filter cubicles. One of the rectifier transformers was tested under full input voltage short-circuit condition. This type test revealed a manufacturing shortcoming on the two secondary coils mounted on the same leg of the magnetic circuit. Lack of reinforcing the ends of the windings made them crush under the strong axial forces of the short-circuit conditions. The test was stopped before any catastrophic failure occurred. Nevertheless, all the coils had to be repaired. In addition to the factory tests, tests will be carried out on the completely assembled converters in the equipment buildings of LEP points 1, 2 and 6.

The remaining 232 unipolar power converters with an upper d.c. output power of 252 kW were subdivided into three sets.

The first one consists of mains commutated six- or twelve-pulse thyristor units with rectifier transformers for the adaptation to the required d.c. output voltage and passive choke-capacitor filters. There are nine different types. The twelve-pulse units are foreseen for changing from parallel to series connection and vice-versa in view of the utilization for Phase 2 (100 GeV per beam) of LEP. All these units were delivered by the end of 1987.

The second set was designed as a compact modular system with four 37 kW converters and their control electronics packed into one cubicle. The specification asked for a high-frequency resonance type of converter. The output stage is transformer coupled and the d.c. power is available at three different voltage levels (125 V - 300 A, 188 V - 200 A, 250 V - 150 A) which gives a good adaptation to a wide range of magnet loads. Two converters can also be connected in parallel. After successful completion of the prototype, the first of the series arrived at CERN early in 1988.

Special attention was paid to the third set, the nine high-current d.c. converters (2000 A, 10 V) feeding the superconducting quadrupoles for the low- $\beta$  insertion. The multi-transformer output stage, which includes rectification and filtering of the switch-mode converter is of a rather special design. The specification pointed out the special requirements of a superconducting magnet and its high stored energy.

The bipolar four-quadrant power converters are of two types : one of 700 W, the other one of 3.7 kW. In both cases the quantities are considerable : 550 and 52 units respectively. Both specifications not only gave the basic design but also stressed the points of reliability, efficiency and reduced weight. The latter was specially important for the 550 switch-mode units which had to form a mechanical unit together with

the electronics chassis in order to ease handling. The 3.7 kW units are of the dual converter type, i.e. they consist of two thyristor bridges in anti-parallel. The first set of fifty 700 W units has been delivered to CERN by end of '87. All the 3.7 kW converters arrived by the same date.

The d.c. current transformers and their associated high-precision circuits as well as the d.c. shunts, both used to measure the output currents, were specified in detail. The required high stability and reproducibility under a wide range of ambient conditions, was achieved as was proven by rigorous acceptance tests. All three orders were terminated during 1987.

The power converters for the conventional coil of the L3 experimental magnet (31000 A, 150 V) and for the OPAL compensator coils (3500 A, 70 V) were specified. These orders were placed early in 1987.

### Control electronics

The standard electronics of the EUROPE type consists of a wide range of modules, extending from high-precision analogue feedback loops to microprocessor-controlled digital circuits, plugged into a six-unit high chassis. The overall specification, covering 860 chassis and about 10000 electronic modules, not only contained the details necessary for the production of the units but also specified the quality assurance procedures to be followed. This included incoming inspection, in-situ testing, burn-in at elevated temperature etc. The first tests with the standard electronics incorporated in the power converters showed very good behaviour, but only long-term operational experience will show the full benefits of a continuous reliability effort. By end of '87, about 50% of the equipment was delivered to CERN. A series of minor orders were placed for the manufacture of small series of specialized modules to cover the special needs for the high power converters.

The incorporated local intelligence calls for a very extensive effort on software. It has not only to handle all the control tasks directly related to the operation of the converter such as commanding the reference source to act as a dynamic function generator and to perform a wide variety of supervisory duties, but also to handle the incoming and outgoing traffic of the computer control system via the multidrop highway. It is worth remembering that the microprocessor based equipment is located inside the power converter and that a considerable amount of effort was necessary to avoid disturbance due to electromagnetic interference.

A 16-bit digital-to-analogue converter is used as reference source for the current controlled converters. For questions of price economy, a hybrid version of such a device was chosen. This was preceded by long and detailed investigations on products from different manufacturers. Surprisingly, the device chosen after competitive tendering showed a long-term degradation, due to insufficient passivation of some of its active components and pollution from its plastic encapsulation material. It is expected that a ceramic package will cure this problem.

### The converters for the RF klystrons

Extensive tests under various output conditions carried out on the preproduction prototype proved the validity of the design concept. These tests included a full power run of the test string, consisting of two RF klystrons and sixteen accelerator cavities. For memory, it is worth recalling the four main parts of each converter of 100 kV, 40 A d.c. output :

- step-down transformers (18 kV to 1 kV)
- thyristor a.c. regulator and its electronics
- high-voltage transformers (1 kV to 52 kV)
- diode rectifier and filter-choke unit.

This unit has now been moved from the test area to LEP point 2 to feed the first set of RF cavities installed in the tunnel.

The specifications used for the preproduction prototype were slightly amended in order to include the experience gained during the test phase and were sent to industry in the call for tenders for the nine sets. A special effort was made to ensure that several suppliers could make an offer and therefore avoid single source problems. All the main components were ordered during 1987 and by the end of the year the oil-immersed units of the first converter were assembled on the test site. Tests started early in 1988 and the other units will follow at intervals of two months.

100 kV, 40 A d.c. cables are used to connect the H.V. converters located at the surface to the loads located in the underground klystron galleries. These H.V. cables had to satisfy, in addition to the very stringent electrical requirements, a set of safety conditions related to their use in an underground area. They had not only to be fire retardant but should not give off, in case of fire, smoke, toxic or corrosive gases. Tests at the manufacturer and in a full scale trial installation at CERN proved that all those requirements were fully satisfied.

#### The converters for the sputter-ion pumps

Nearly 330 converters were recuperated from the ISR, reconditioned and adapted to feed sputter-ion pumps for the LEP vacuum system. For the additional 400 new converters, all the H.V. components were specified very carefully and separate orders placed after successful tests of the pre-production prototype. The required d.c. output characteristics depend largely on the electromechanical stability of the magnetic circuit of the transformer and in particular of its shunt. Therefore, the manufacture of the core and specially its impregnation had to be monitored in detail.

#### Quality assurance

Good quality and long-term reliability are a continuous battle. The product has not only to be designed keeping in mind this aim but the details of the design of the manufacturer as well as the manufacturing procedure have to be monitored continuously. Complete factory tests, including type tests, were carried out in the presence of a CERN representative. They were based on extensive use of computer controlled automatic test equipment. The overall performance of the equipments was checked carefully on the CERN site. Up to now these tests showed clearly that the majority of the suppliers followed carefully the quality instructions. Some component defects nevertheless showed up on long-term tests. One of them was the DAC problem, mentioned earlier, the others were contactor problems, electromagnetic interference etc. System tests will follow, first on the level of equipment buildings, later from the LEP Main Control Room. Operational experience will prove the validity of the quality measures carried out during this project.

#### Acknowledgements

My thanks go to all the members of the LEP Power Conversion Group for their devotion in the conception and subsequent realisation of the power

converters. I would like to express my appreciation to all the industrial firms and the members of the other LEP groups who help efficiently in the construction and handling of all this sophisticated equipment.

#### References

- 1) "Design Study of a 15 to 100 GeV  $e^+ e^-$  Colliding Beam Machine (LEP)" - The LEP Study Group, CERN/ISR-LEP/78-17, August 1978.
- 2) "Design Study of a 22 to 130 GeV  $e^+ e^-$  Colliding Beam Machine (LEP)" - The LEP Study Group, CERN/ISR-LEP/89-33, August 1979.
- 3) "LEP Design Report", Chapter 7 : Power Converters. CERN-LEP/84-01, June 1984.
- 4) H. W. Isch, "The CERN-LEP Project and its DC Power Supplies" - Proceedings PCI Conference, Geneva, September 1982, p. 278.
- 5) J.G. Pett, "Integrating Local Intelligence into LEP Power Supplies" - Proceedings PCI Conference, Geneva, September 1982, p. 292.
- 6) P. Proudlock, "The Medium Power Auxiliary Magnet Power Supplies for LEP ; can Switch-Mode meet the challenge ?" - Proceedings PCI Conference, Geneva, September 1982, p. 297.
- 7) H.W. Isch, J.G. Pett, P. Proudlock, "CERN Power Converter Requirements and Topologies for the LEP Machine" - Proceedings International PCI/MOTORCON '83 Conference, Orlando, April 1983, p. 292.
- 8) M. Boidin, H. Foch, P. Proudlock, "The Design, Construction and Evaluation of a New Generation High-Frequency 40 kW DC Converter" - Proceedings of the Ninth International PCI Conference, Paris, October 1984, p. 124.
- 9) H. W. Isch, J. G. Pett, P. Proudlock, "An Overview of the LEP Power Converter System" - Proceedings of the IEEE Particle Accelerator Conference, Washington, March 1987, Vol. 3, p. 1399.
- 10) A. Beuret and J. G. Pett, "Dynamic Behaviour of the LEP Power Converters" - Proceedings of the IEEE Particle Accelerator Conference, Washington, March 1987, Vol. 3, p. 1440.
- 11) H. W. Isch, J. G. Pett and P. Proudlock, "The use of Switch-Mode Power Converters for the LEP Main Ring Power Converter System" - Proceedings of the IEEE Particle Accelerator Conference, Washington, March 1987, Vol. 3, p. 1511.
- 12) F. Bordry, H. W. Isch, P. Proudlock, "Computer-Aided Analysis of Electronic Power Converters ; Simulation of a High-Voltage Power Converter" - 6th IEEE Pulsed Power Conference, Arlington, July 1987.
- 13) A. Delizée, K. Dahlerup-Petersen, "A 4MW - 100 kV DC Liquid Load and a Rapid Recycling Crowbar System for the Evaluation of the Klystron Power Converter of the LEP - CERN", - 6th IEEE Pulsed Power Conference, Arlington, July 1987.
- 14) A. Beuret, F. Bordry, P. Proudlock, "Numerical Simulation of Thyristor Power Converters taking into consideration the Firing-Circuits and the Closed-Loop Control" - 12th IMAC World Congress on Scientific Computation, Paris, July 1988.