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The prototype realization, the series production, the commissioning on the LEP site and the first operational results of power converters are presented.

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Abstract

For feeding the LEP klystrons, a series of 10 D.C. power converters was built according to the CERN design of a 100 kV, 4 MW pre-series unit. The power converters are fully voltage regulated and are capable of withstanding regularly short-circuits on their outputs as a normal operation mode.

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Introduction

For stage one of LEP, beam energies up to 55 GeV were achieved by 128 accelerating radio frequency cavities fed by a total of 16 CW klystrons (1 MW each at 352 MHz).

Studies were carried out to find the optimum topology for the power converters taking into account such contradictory aspects as : LEP budget constraints, operation of the RF system and long-term reliability requirements. The various circuits possibilities were simulated by the general iterative program Script [1, 2]. Finally, it was chosen to feed two klystrons by one power converter (output range 0 to 100 kV at any current from 0 to 40 A).

A pre-series power converter was built, with a thyristor A.C. line controller, to verify its ability of operation under the following conditions : a variable practically resistive load, repetitive klystron arcings or short-circuits at its output (short-circuit power ~35 MVA) and large mains fluctuations. The internal flashover of klystrons is cleared by phasing back safely the thyristors of the A.C. controller. Repetitive power converter short-circuits should not cause any degradation, either mechanical or electrical, on the components life duration of at least 10 years.

Power Circuit Diagram

The power converter is composed of 4 units (Fig. 1): a step-down transformer TR1/2 (18/1 kV, 2 x 3 MVA, impedance voltage U_z = 6.5%), a thyristor A.C. line regulator and its electronics, a high-voltage transformer TR3/4 (1/52 kV, 2 x 3 MVA, U_z = 6.5%) and a diode rectifier-filter choke unit.

TR1/2 is fed from the 18 kV, 50 Hz, three-phase mains. Their secondaries form a three-phase system shifted in phase by 30° electrical to obtain a twelve-pulse system at the converter outputs. An A.C. regulator is connected between TR1/2 and TR3/4. The four thyristors modules are anti-parallel configuration. Power thyristors are controlled by a twelve-pulse firing circuit ASAD, having a fast open-loop response. The regulation of the output voltage and the overcurrent protection are realized by two cascaded-loops. A high-voltage divider

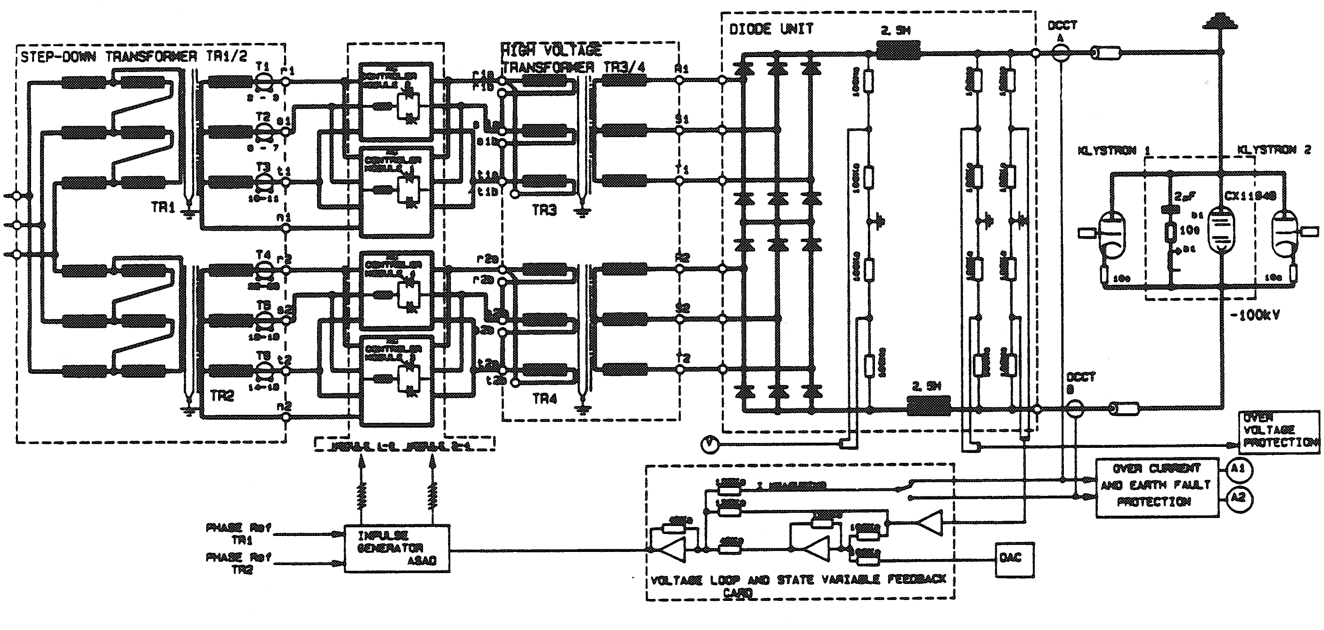

Fig. 1 Power Circuit Diagram

output is adjusted to the reference delivered by a remote-controlled DAC and, in addition, a compensation of the passive filter (5 H, 2 μF) is given by a state variable feedback.

The diode rectifier is an assembly of 12 arms of selected avalanche diodes wired in series. The passive filter (resonance frequency 50.3 Hz) is made of two chokes of 2.5 H connected symmetrically and a filter capacitor located in the klystron gallery via two coaxial XLPE cables of 500 m length maximum. Two DCCT's mounted on each H.V. coaxial cable are used for earth current fault detection and overcurrent protection. The power circuit is earthed at the collectors of the klystrons. A double cathode thyratron switch is employed as a klystron crowbar and limits the klystron fault energy to 50 J.

Power Converter Construction and Component Evaluation

TR1/2, TR3/4 and diode rectifier filter chokes unit are housed in three separate tanks filled with mineral oil and are oil natural/air natural cooled; all the units are shielded. Six oil-filled stainless steel ducts link TR3/4 to the diode rectifier unit so, avoiding twelve high-voltage connectors (air or SF6). Nevertheless, this connection requires a tight mechanical tolerance on the assembled units. This inconvenience is largely compensated by a standard TR3/4 transformer construction, a quick operational dismounting of the diode rectifier unit and a separated cooling of the units (transformer oil not polluted by an eventual flashover inside the diode unit). All three tanks are vacuum tight and checked at 0.3 bar. The diode rectifier filter chokes unit is mounted on a movable slip with height adjustments. IEC impulse tests were performed respectively at 125 kV for TR1/2 and 450 kV for TR3/4.

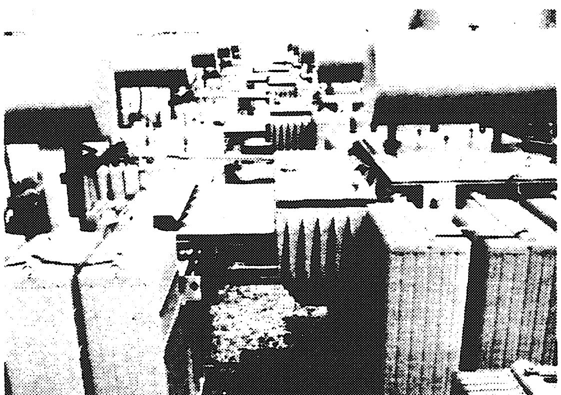

Fig. 2 Power Converter View

To verify the transformer ability to withstand short-circuits, as a normal duty, a sequence of 18 short-circuits of 0.5 s duration were made on two sets of transformer units. The short-circuit reactance was only altered by 0.5%. After de-tanking a slight bend on the bars of the low-voltage coils and on a bushing connection was observed; a reinforcement of the structure cured this problem.

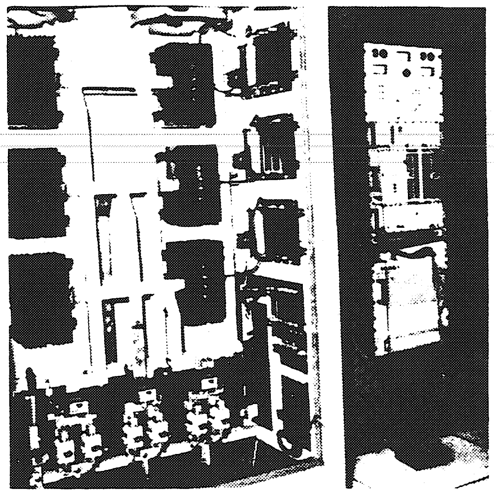

Fig. 3 A.C. Regulator View

The A.C. regulator cubicle is divided in three parts (Fig. 3) : two series of two thyristor modules and the electronic chassis with Europe cards for regulation, interlocking and remote control. Six discs type thyristors MEDL-DCR 1476SV (3400 V), of an active silicon chip of 75 mm Ø, are used per module. Due to our particular application with large repetitive overcurrent, additional tests were performed at 12000 A peak (2000 cycles of half sine wave current with 1500 V r.m.s., 50 Hz reapplied). Each thyristor is assembled on a heat sink providing a double-sided cooling by natural air and limiting the junction temperature at 125°C. Many tests were also done to cure the pitting of the surface contact observed at high peak currents. Good results were obtained with a machined surface finish better than 1.6 μm (ISO N7) followed by a surface nickel plated to a depth of 8 to 15 μm.

The two high-voltage chokes are designed for a 50°C maximum winding temperature rise and for a capacitance per choke of less than 1.1 nF (limitation of parasitic oscillations). One choke is made of two coils and two limbs core of steel grain orientated laminations with distributed air-gaps. The inductance is 2.5 H at nominal current I_n = 40 A (1.8 H at 1.5 I_n and 0.4 H at 10 I_n). IEC impulse tests were performed at 450 kV. Both chokes are attached to the lid of the tank (as well as the diode rectifier).

The diodes IR 70 HA 160 were carefully selected per arm of 56 units anode to case, and 56 units cathode to case according to the following criteria : avalanche voltage 1.9 kV min., avalanche characteristic at 125°C junction temperature, reverse recovery charge within one band for one arm (10 μ cb variation), overload peak forward half sine wave current 360 A for respectively 10 and 150 ms and a burn-in test of 24 hours at 1.6 kV (150°C junction temperature) followed by a leak test. Sampling tests of about 5% of the series production were performed on every batch of 1500 diodes. No failure occurred on the production of 16500 diodes. Diodes are assembled by pair on an aluminium cooling fin (Fig. 4) which is designed for a 105°C maximum junction temperature. An equalizing network is wired across each diode (series 0.68 K - 50 nF and parallel 700 K). Fifty-six pre-wired heat sinks are assembled on an epoxy bar to form one arm. Tests on each arm were performed at 150 kV and on each diode at 1.8 kV. An insulating cylinder is mounted around each arm to improve the heat exchange.

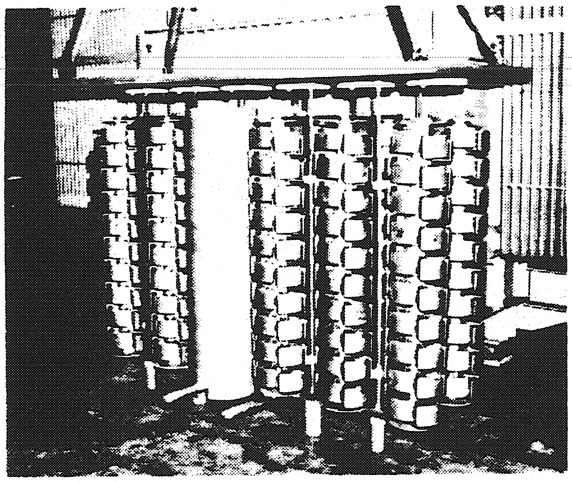

Fig. 4 Diode Rectifier Arms

Power Converter Performance

All power converters were evaluated, prior to the LEP installation, in a special set-up, equipped with a variable 4 MW D.C. liquid load and three spark-gaps, both simulating two klystrons at full load and klystron arcing mode [3].

The peak-line inrush current was 2200 A. Current wave-forms IL (Fig. 1) in the thyristor line is given at Fig. 5 at full load. The current for one thyristor module is 780 A r.m.s. and 1560 A r.m.s. for TR1 or TR2 secondary winding. Each thyristor is individually connected to its transformer winding (TR1/2 secondaries and TR3/4 primaries) so getting a reasonable current equilibrium (Fig. 1); the maximum variation of the other units (reference to module 1 and phase R) was between - 4.6 and 5%.

The D.C. output voltage error compared to the DAC settings is 0.2% maximum for an output range of 50 to 100 kV. The long-term output stability is better than 0.8%.

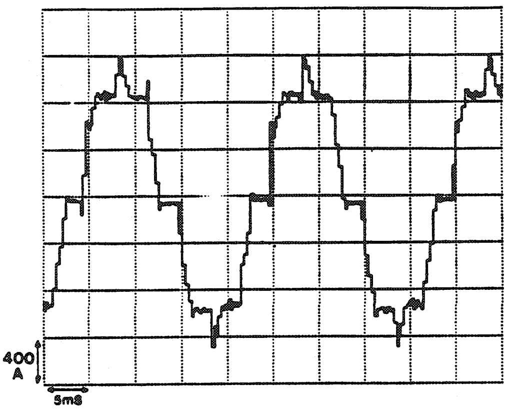

Fig. 5 Line Current I of Thyristor Module at 100 kV, 40 A

The compensation of the passive filter given by the variable state feedback is shown on Fig. 6 for the frequency analysis and at Fig. 7 for the time response of the loop (D.C. step of 20 kV); the transient voltage of 10 kV peak is suppressed.

A full load test was performed during 24 hours to verify the correct functioning of each power converter. The measured temperature of thyristor heat sink was 70°C maximum at 25°C ambient (95°C maximum on thyristor junction). The oil temperature (27°C ambient) was respectively 50°C maximum on the tank TR3/4 and 48°C maximum on the diode rectifier tank (90°C maximum on diode junction). Mains perturbation response was checked by switching on a 8 MW transformer connected on the same line; it was observed a peak D.C. output voltage overshoot of about 10% for 15 ms.

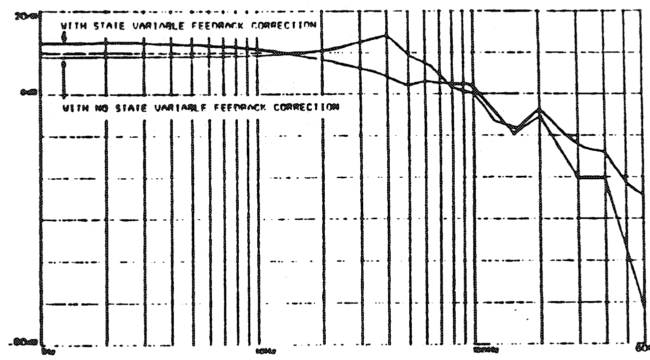

Fig. 6 Loop Frequential Analysis at 70 kV, 20 A

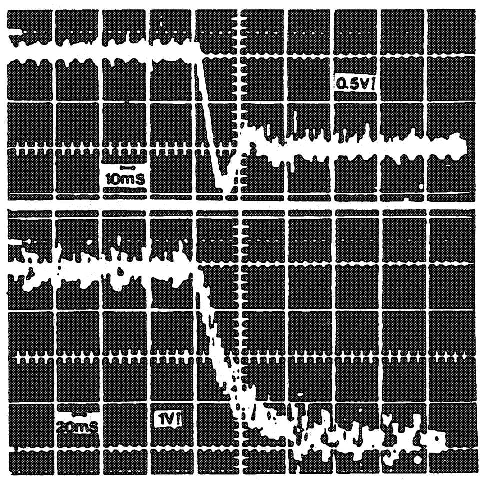

Fig. 7 Step Function Response

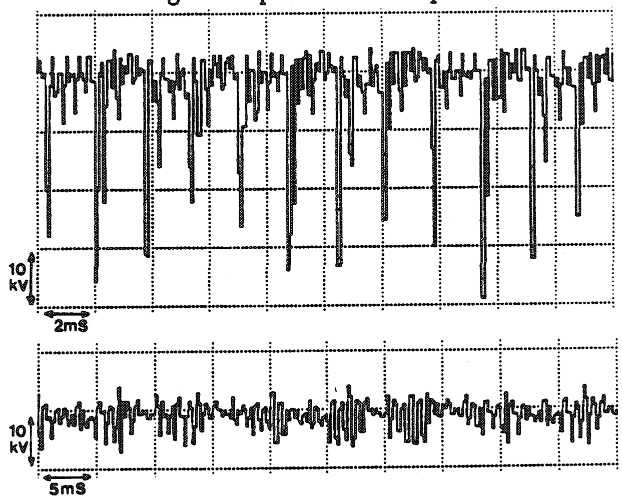

Fig. 8 Parasitic Oscillation at the Voltage Loop Input

The difference between chokes connection as on Fig. 1 and two chokes in series in one H.V. side was also verified; the parasitic oscillation seen by the regulating loop with the connection of Fig. 1 is reduced by a factor four (Fig. 8).

After the heat run, power converters were submitted several times to short-circuited outputs (spark-gap firing). The switch-off sequence by blocking the thyristor firing pulses is given with crowbar firing at Fig. 9.

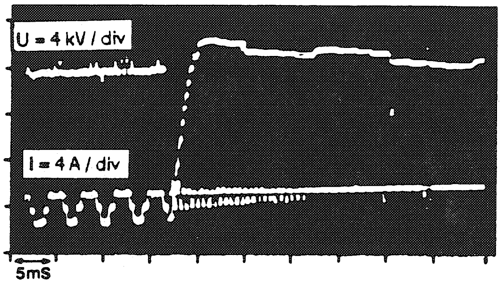

Fig. 9 Crowbar of Power Converter

LEP Commissioning and Operational Results

The ten power converters installed in the LEP buildings (Fig. 11) were verified at 100 kV maximum and on a 1 MW air load before connecting to the klystron circuits.

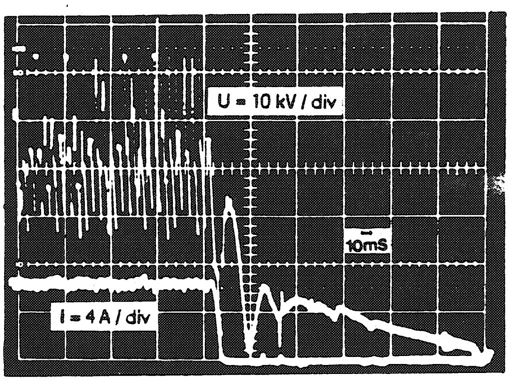

Fig. 10 Crowbar (thyratron) of Power Converter

In the klystron fault mode, the relation output voltage versus D.C. overcurrent transient depends on thyristor blocking time, on the sine wave cycle and on the thyratron (crowbar) firings. A typical sequence klystron arcing, crowbar firing, seen by the power converter is shown at Fig. 10; the observed peak D.C. overcurrent is 150 Amax. In LEP commissioning, difficulties occurred due to the inrush current at the 18 kV mains breaker closure. A pre-magnetisation circuit (transformer 9 kVA) was installed in the secondaries of TR1/2. The peak inrush current of 2200 A was reduced to practically zero.

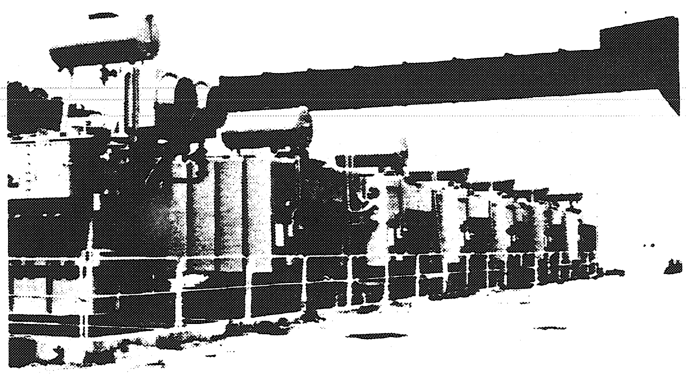

Fig. 11 LEP Power Converter Installation

Since June 1989, the beginning of LEP phase 1 operation, each power converter has run at least 5000 hours with 24/24 hours duty during several weeks and with 50% of time at full load. It was estimated that a total of 2000 power converter switch-offs (by overcurrent and/or klystron arcing) were made safely and without current switching by the 18 kV mains breaker openings. All power converters have shown a correct functioning and to this day no fault has been observed.

Conclusions

The first operational results have demonstrated the validity of our design and construction. The feeding of two klystrons by one power converter was done at a particularly reasonable cost per unit of about k$ 480. The reliability obtained gives us confidence for the long term operation. For LEP Phase 2 (increase beam energies up to 100 GeV), a second series of 10 power converters are under construction with the same design.

References

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