SWITCH MODE POWER CONVERTERS; PRESENT AND FUTURE

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Abstract

More than 600 switch mode power converters are installed in LEP to power the Main Ring Magnet System. The horizontal and vertical corrector magnets are fed by 520 bipolar, four-quadrant units of 675 W output rating. The short chains of quadrupole and sextupole magnets with copper windings are powered by 105 modular resonant type power converters of a d.c. output rating of 37.5 kW. Their transformer-coupled output stage allows to choose three different output ratings, i.e.: 300 A/125 V, 200 A/188 V and 150 A/250 V. Eight high current 2000 A, 10 V converters feed the superconducting quadrupoles for the low-ß insertions in the physics interaction regions. Details will be given on the initial CERN design work leading to the choice of circuit topology, in order to meet the strict accelerator requirements, particularly on efficiency, size and reliability. The converters were purchased from European Industry on the basis of precise performance specifications. High power switch mode converters of compact design and high efficiency are by now an established technology, which offers attractive technical and economic solutions for powering conventional and superconducting magnet systems.

Introduction

LEP, the Large Electron Positron Collider, is a completely new machine spread over a very large site which had to be built, and will eventually be run, with limited finances and man-power. These constraints were applied to the conception of the Power Converter System from the very beginning. New technologies, such as switch mode converters, had to be considered seriously since buildings and other infrastructure surrounding the converters were certain to be reduced. The long distances for communication meant that local intelligence would have to be located within the converters. They had to be designed for initial operation at 65 GeV with minimum cost, while being extendable to 100 GeV with no waste. Switch mode converters, with their reduced volume and modular approach, therefore seemed very attractive.

Working with European Industry and Universities

By the beginning of the 1980's switch mode conversion techniques were becoming well established following the incentives given by the energy crisis of the 1970's. Could the new switching devices be applied successfully to the accelerator environment and if so to what power levels? New more powerful and faster switches seemed to be springing onto the market every day.

It was good fortune that in 1982 the Power Conversion International conference and exhibition visited Geneva. The LEP Power Conversion Group were there with a stand and papers to benefit from the gathered expertise. This allowed close contacts to be established with both industry and academic institutes thus launching a programme of prototype evaluation. Where industry could provide ready made prototypes they were borrowed or bought at low cost. If not, they were made at CERN.

CERN needed to investigate the types of topology that might be applicable to LEP, establish the upper power limits, study microprocessor integration into switch mode environments, evaluate performance on magnet loads, look into reliability, and study likely space and cost savings.

At the end of this period of evaluation we had learnt :

- how to drive and use Mosfets, GTO's, Large Bipolars, RCT's, etc...
- how to reduce EMI to acceptable levels for microprocessor integration and p.p.m. loop performance
- how to design HF magnetic elements, (transformers, chokes).

We had also established :

- the dynamic and static performance advantages
- the need for HF galvanic isolation for electrical noise reduction and for safety reasons,
- that up to 40 kW could be attained
- which type of topology would be applicable
- how to split up the contracts.

Tendering

The preliminary enquiry, sent out to 410 manufacturers in Europe, covered all the power converters for the magnets of the LEP main ring. It contained pertinent questions in the sections dealing with types that could be switch mode. The replies, as well as further pressures to reduce building sizes, led to the adoption of switch mode technology for the following three types :

Type	Qty	Output		Power	DC precision	Oper. Freq. (kHz)	Range	Eff. at max (%)	Vol. (m^3)	Weight (kg)
		U (V)	I (A)	(kW)						
C	105	125 188 250	300 200 150	37.5	$\pm 1x10^{-4}$	11	17:1	90	0.474	232
D	8	10	2000	20	$\pm 1x10^{-4}$	20	4:1	80	0.8	400
F	520	±135	± 5	0.675	$\pm 5x10^{-4}$	50	1000:1	80	0.034	15

Detailed but realistic performance specifications were issued for each type having the widest possible appeal to industry. While CERN suggested suitable topologies and block diagrams, the manufacturers were always free to propose alternative solutions according to their own experience. There was a very good level of interest in the specifications and a higher than expected number of replies.

Converters of Type C

These converters are the keystones in the future upgrading of the LEP Power Converter System. Using the same 37.5 kW inverter powered directly from the 380 V three-phase mains, they were to have three output modules as shown above. They also had to be capable of being paralleled to give 75 kW output. In this way all converters used for LEP 1 could be re-used in LEP 2.

Qualifying prototypes were ordered from industry and the final contract placed with Alsthom TRV, Villeurbanne, Lyon, France.

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Series-resonant converters had for a long time seemed attractive, particularly because of their elegant commutation modes which allowed slower and more robust switches to be used, and they generally suffered less from EMI problems. However, to obtain a large output range, which was necessary in this application, caused large frequency variations or discontinuous operation. Neither were desirable.

Alsthom's solution was to propose a double resonant converter (Fig. 1). (This design is the subject of an Alsthom patent.) Using GTO's in a zero-turn off mode, the inverter works between a minimum frequency of 7.1 kHz, where it produces 17 W, and a maximum of 11.1 kHz for 37.5 kW. The desired power can be obtained from a half H-bridge. Hence this topology could be used at even higher power levels. The whole converter is contained in three modules, each 0.52 m wide, 0.44 m high and 0.69 m deep. The total weight of one converter is 232 kg. Four converters are located in one cubicle measuring 3.28 x 0.9 x 2.06 m. The efficiency is around 90% from 10 kW to 37.5 kW.

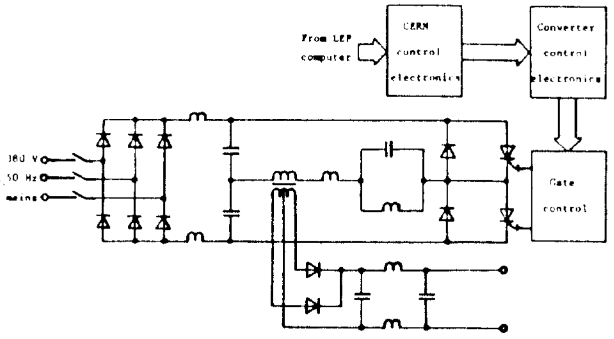

Fig.1 Schematic of double resonant converter

Converters of Type D

The type D converters were destined to supply the superconducting magnets of the Low-β insertions of LEP. If compact, high-efficiency switch mode units of 2000 A, 10 V could be made then they could be placed underground close to the magnets. This would save considerably on DC cabling costs and the power rating of the converters themselves. With the ever increasing use of superconducting magnets in accelerators, this became an important project for the future, not only for LEP but also for other new accelerators.

Again, qualifying prototypes were ordered from industry and tested for suitability when powering superconducting magnets. The results were encouraging and a contract was placed with Jema, San Sebastian, Spain, for the series production.

Their expertise had been developed around an H bridge inverter using Mosfet transistors. They therefore proposed the solution shown in figure 2. Since the bridge had been designed using earlier available Mosfets, a small auto-transformer was used at the input so that the nominal DC rail voltage of the two inverters was 370 V. The inverters each feed 3 HF transformers connected in series on the primary, all secondaries being paralleled via low-loss schottky diodes to the output filter. The inverters operate at 20 kHz and use PWM.

The power part, which has a volume of 0.8 m^3 and is air-cooled by low-speed fans, is located in a standard 19-inch rack. Efficiency at 2000 A, 10 V, is 80%, while at 2000 A, 3 V, it is 55%.

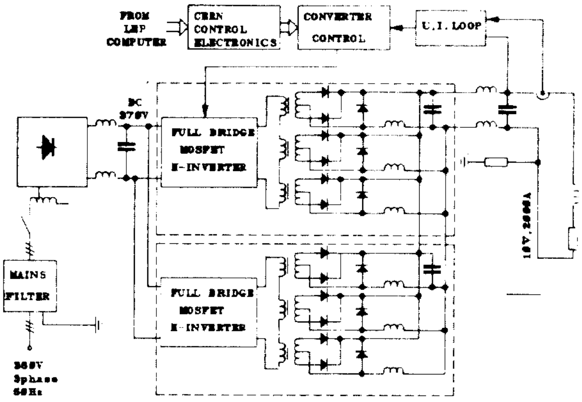

Fig. 2 Schematic of 2000 A, 10 V Type D

Converters of Type F

These converters were to power the horizontal and vertical corrector magnets of LEP. The 520 dipole magnets are distributed along the entire 27 km length of the machine and are used to perform localized fine steering of the beams. The converters therefore had to be true bipolar devices with the highest possible voltage and lowest current so as to minimize cabling costs.

After competitive tendering, the contract was placed with GEC, Stafford, G.B. Their design is shown in figure 3.

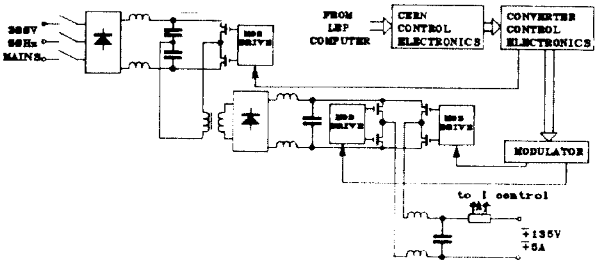

Fig. 3 Schematic of the bipolar F type

It consists of a half bridge Mosfet inverter working directly off the rectified 380 V three-phase mains. This inverter supplies, via an HF isolating transformer and rectifier, the DC rails of a four-quadrant switching inverter again consisting of Mosfets The two inverters are synchronized, but only the output inverter is used for control. Operating at 50 kHz and 50:50 mark to space, it gives zero output. By varying the mark to space either positive or negative output can be achieved with a smooth transition through zero. The stored magnet energy can be dissipated in a power dump on the DC link or in transient suppressors of 280 V in the case of failure.

The power part of the converter is housed in a box 445 mm wide, 263 mm high and 290 mm deep. The total weight is 15 kg.

In view of the high numbers involved, a pre-series of 20 converters were manufactured and fully evaluated at CERN. Much work was carried out on these units to eliminate both technical and production problems. The series units could thus be manufactured without any modification which should further increase reliability.

Now that the equipment arrives at CERN

In general the units have been designed as voltage sources by the manufacturers. The precision current loops, as well as the control and diagnostic intelligence, are added at CERN during provisional acceptance. With the experience gained in the earlier prototype work, the problems encountered in keeping up with the series production were only minor and we are now in a stage of smooth installation and commissioning. All units are completely and thoroughly tested in a central test area before transportation to their final equipment buildings. Once installed, commissioning is rapid and usually trouble-free.

First tests on a beam

In July 1988, injection tests were carried out in octant 1-2 of LEP. These tests were controlled from the LEP/SPS control room and a beam of positrons transferred along nearly 3 km of the LEP tunnel. These tests used 8 of the type C converters powering individual quadrupoles and 47 of the type F on correctors. All units, consisting of their switch mode power parts, microprocessor and software, performed without problems. The beam suffered no ill effects from the presence of the switch mode converters, but on the contrary benefited from their superior transient performance.

Reliability during the acceptance tests, cold check-outs and actual injection tests have been above our expectations.

Future trends

The development of high power inverters working at tens of kHz, as in the C types, has opened up a new modular approach to power converters for accelerators. By changing the passive DC output stage, (transformer, rectifier and passive filter) practically any combination of volts and amperes can be achieved. The added possibility of parallel or series connections further broadens the scope. A 'standard' inverter could thus become the building block of a wide variety of different converters. It would also seem that powers approaching 100 kW will soon be available.

The D types have shown the usefulness of switch mode technologies in powering superconducting magnets. Again, there is no reason why several units cannot be operated in parallel, thus supplying several thousands of amperes if necessary. There also exists the possibility of powering individual superconducting magnets, with units located very close to the magnet and perhaps powered from the d.c. busbars of a chain of magnets.

The F types have shown that specialized switch mode converters can be made in large series with high levels of reliability and repeatability. They are ideally suited to the powering of small corrector magnets.

If reliability has ever been in question, it has nearly always involved the switches. Drive circuit failure is often fatal for the power devices because of their need for active drives. Better drive circuits are being designed every day, and with more robust and safer switches finding their way onto the market these problems should diminish. The passive elements, such as transformers, chokes and capacitors, are undergoing the same trends.

CERN was fortunate that it was buying in reasonably large quantities. There still remains the problem of the 'one or two off'. Manufacturers are just not willing to undertake such small quantities, because of the design and prototype effort needed. It also has to be admitted that the number of experienced manufacturers is limited. There is also the uncertain area of patents, which makes it difficult to establish a standard topology which can be used by several manufacturers. Standard topologies reduce staff training needs, and ease operation and maintenance.

However, many of the above problems were encountered with the first high-precision thyristor units. It can only be assumed that, as then, time will find the solutions once such topologies become public property and manufacturers become more experienced.

Conclusions

We have certainly been encouraged by the experience of installing switch mode into LEP. They have shown that powers up to 40 kW can be reliably achieved and that problems of EMI and microprocessor integration can be dealt with. They have allowed us to lodge the converters in less volume, and to reduce the cooling costs. With their high dynamic performance, the beams can be much better isolated from the effects of mains disturbances. It is even possible to design the units to remain within specification with a total single phase loss of 100 ms. With well designed input stages, they will operate at near unity power factor, with a low level of mains harmonic distortion.

With these quantities the prices were similar to those for conventional equipment. Taken overall however, from a system point of view, then costs have been reduced.

Acknowledgements

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