NOVEL BIPOLAR POWER CONVERTER FOR CORRECTOR MAGNETS

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Abstract

A switch-mode power converter was chosen to power the LEP corrector magnets. The topology used provided a naturally bipolar output with smooth passage through zero current, without the time delays and unreliability of electro-mechanical switches previously employed to accomplish this task. The large numbers involved (520) dictated the need for high reliability, which has been achieved and recent performance statistics have proven.

Introduction

CERN, Geneva, has a requirement for bipolar power converters to power the horizontal and vertical corrector magnets of LEP (the Large Electron Positron collider). There are 520 corrector magnets installed in the 27 km circumference tunnel and they are used to correct the orbits of the electron and positron particles.

There are two corrector magnet types (horizontal and vertical) each with two maximum current ratings (2.5 A and 5.0 A). This together with the various cable lengths from the magnet in the underground tunnel to the power converter in the surface building presents a whole range of time constant (L/R) loads to the power converter.

The power part of the converter was specified by the LEP-PC group of CERN (now SL-PC) and designed and manufactured by industry. The LEP-PC group designed the precision control and remote control electronics which was built by industry.

Choice of Technology

Past experience with collider machines (the ISR at CERN) had proven the necessity for high reliability, particularly for corrector elements which are often in large numbers, often have to work close to zero current outputs and are often solicited during a physics run to maintain the best conditions for data taking.

In the past, the bipolar nature was provided by an electro-mechanical switch, acting as a polarity reversal switch on the output of a unipolar power converter (Fig. 1). This had many disadvantages from a machine operations point of view :

i) electro-mechanical switches are unreliable and need maintenance;

ii) electro-mechanical switches take time to change state, which is increased further by the necessity for protection circuits to ensure current zero before changing state;

iii) the unipolar power converter has difficulties in providing current outputs close to zero in value and these often drift with time. Hence, steps in current when changing polarity around zero, and subsequent partial beam losses.

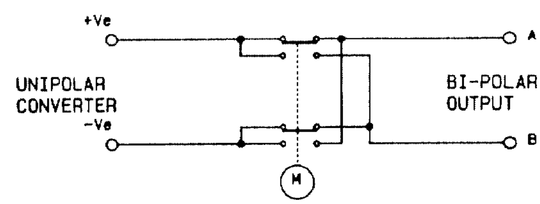

Fig. 1 Traditional Bipolar Power Converter

The requirements for LEP, of a large number of corrector magnets, and the necessity for synchronised ramping of all power converters during acceleration of the particle beams, dictated a high-reliability with very low or preferably zero transit time from one polarity to the other. Low cost and low weight were other factors in the design criteria.

Fortunately during the study period (the early 80's) switch-mode technology for power converters in this power range (< 1 kW) were beginning to be discussed. These were normally unipolar stabilised voltage output bench type power converters, but one of the topologies used lent itself for bipolar use.

This was the H-bridge, which for power converter designers today is a well known concept. It is however novel in its application as a bipolar power converter for magnets in an accelerator. It replies to the technical criteria set out above, in that :

- zero is part of its operational range between full positive and full negative output;
- it does not have the unreliable electro-mechanical switch;
- it has low weight, therefore easier for quick replacement;
- it has extremely low transit time through zero;
- it is cheaper or comparable to the cost of conventional designs.

Having chosen this design concept mainly for its technical merits, it was now up to CERN to build in the high reliability.

Brief Technical Specification

Mains input :	380 V r.m.s., +10%, -15%, 3 ph, 50 Hz
Mains transients :	any step change within the mains tolerance and one phase missing for 100 ms
D.C. output voltage :	continuously variable from +135 to -135
D.C. output current :	continuously variable from +5 A to -5A (type 1)
Output ripple voltage :	< 0.5 V at 50 Hz < 1.0 V at 100 Hz < 0.1 V above 300 Hz
Efficiency at full power :	> 80%
Weight :	< 20 kg
Output current stability :	better than $\pm 5 \times 10^{-4}$ Imax over 4 hrs better than $\pm 1 \times 10^{-3}$ Imax over 1 week
Range of magnet loads :	L = 7 - 20 H R = 17 - 54 Ω.

Technical Description

The schematic diagram for the power converter is shown in Fig. 2. It consists of :

- 3-phase input stage with fuses for overload protection;
- an RFI filter, to reduce the levels of radio frequency interference injected to the mains to the levels defined in the VDE and IEC norms;
- a contactor for ON/OFF control;
- a diode bridge with passive filter to provide a D.C. source to the inverter stage.

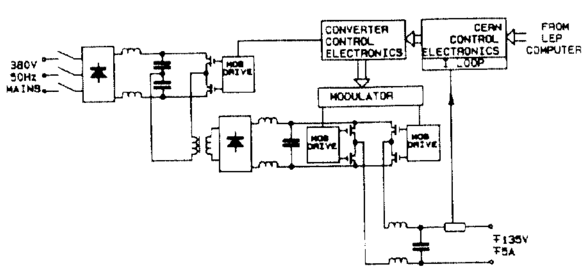

Fig. 2 Schematic of Complete Power Converter

The inverter stage uses a half bridge, split capacitor topology to provide a 50 kHz square wave to the primary high frequency isolation transformer. The greatly reduced size and weight of this transformer (~1/25) is one of the advantages of the switch-mode technique.

The H-bridge chopper stage takes its D.C. feed from the rectified 50 kHz square-wave output of the high-frequency transformer. The operation of the H-bridge is shown in Fig. 3 and can be explained as follows.

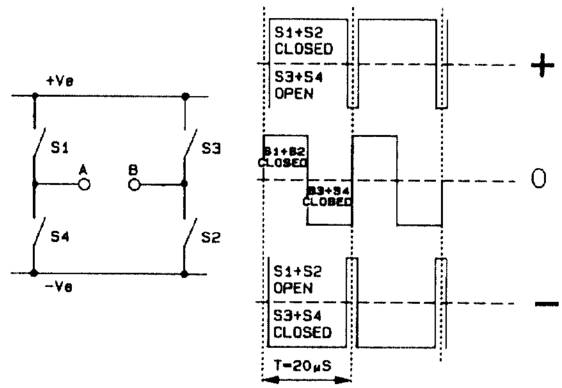

Fig. 3 Schematic of an H-bridge Converter Showing Non-filtered Output Waveforms

If we consider the static case where switches S1 and S2 are closed with S3 and S4 open, we have +ve on A terminal of the magnet and -ve on the B terminal. With S3 and S4 closed and S1 and S2 open we have -ve on A terminal and +ve on B terminal. Now if we alternate between the opening and closing of the pairs of switches S1, S2 and S3, S4 at some high frequency (50 kHz) and maintain the same open and closed times for each pair, we have a square wave A.C. output. If this is heavily filtered by a passive L and C filter, we have zero D.C. output with a small A.C. signal superimposed. By varying the mark (time-on) to space (time-off) ratio of the pairs of switches, whilst maintaining the repetition period, it can be seen that any output from maximum positive to maximum negative with smooth passage through zero can be obtained. The fact that the repetition rate is 50 kHz means that the passive filter chokes and capacitors are very small compared to their 50 Hz equivalents.

The output current is measured via a precision power resistor, the voltage output of which is amplified and compared with the DAC reference by a precision comparator amplifier.

The value of the integrator capacitor and resistors around the comparator are calculated to ensure the high D.C. gain required, as well as to maintain stability of the closed current loop. The values were chosen such that the same control loop could be used for the whole range of corrector magnet and cable configurations of the machine, whilst maintaining the performance requirements, particularly during ramping.

DAC : Digital to Analogue Converter
IEC : International Electro-technical Commission
RFI : Radio Frequency Interference
VDE : Verband Deutscher Elektrotechniker

The current loop being the main precision control, drives the power output stage itself having a voltage feedback loop which virtually eliminates mains disturbances and mains induced ripple [1]. the remote control electronics with its microprocessor driven local intelligence is also housed in the power converter [2].

To improve performance during abnormal mains conditions, considerable energy storage was provided for the power input stage, and particularly for the electronics auxiliary supplies. The microprocessor memory circuits were supplied via super capacitors which keep them active for at least 48 hours.

As a result, the LEP machine has been able to provide data taking conditions during many thunder storms last year, whilst the injector machines have been down.

Reliability

As mentioned previously, reliability of equipment and in particular for the power converters is extremely important for a storage machine.

Reliability can be improved by paying particular attention to the following aspects :

- keeping the design and implementation as simple as possible;
- keeping active protection circuits to a minimum;
- insisting on a high-level of quality control during manufacture;
- full testing of all sub-assemblies as well as complete equipment;
- extensive period of burn-in at elevated ambient temperature.

Because of the relatively new technology of this particular converter CERN also insisted on evaluating a prototype and produced a small number as a pre-series before starting full production.

This procedure takes time and means that machine designers must specify their requirements in time. A power converter is a very important element in the machine performance and reliability and should not be considered as a last minute add-on.

The LEP-PC (SL-PC) group has a policy of working closely with industry both during design and production of their converters. This enables mis-interpretations of the specification to be corrected quickly and at little or no cost to the manufacturer. Industry seems to appreciate this close working relationship and CERN gets a better product.

Operational Experience

Due to the excellent collaboration between industry and CERN for the manufacture of the power converter and its precision resistor for measuring the current, the performance of the converter far exceeds its technical specification and stabilities in the order of 1×10^{-5} Imax have been achieved over several hours. This achievement became a requirement for certain applications.

During the first six months of operation, the failure rate fell steadily from 4% per month to 1% month giving an MTBF (Mean Time Between Failures) per equipment of 20000 hrs to 75000 hrs. Some of these failures could be attributed to very high ambient temperatures as the ventilation system in the buildings was not yet operating correctly. Not all failures produced beam disturbances. Since the start-up of the machine, in March of this year, the failure rate has been well below 1% month.

Conclusions

The choice of a switch-mode bipolar power converter for the corrector magnets of LEP has been proven to be justified, both by the technical and operational advantages offered to the machine and by the reliability obtained.

With the evolution of power semiconductors since the conception of these power converters, it is now feasible to envisage this approach to much higher powers (up to 50 kW), enabling a much higher percentage of machine corrector elements to profit from its advantages.

Acknowledgement

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[2] J.G. Pett, Remote Control of the LEP Power Converters, 2nd EPAC, Nice 1990.