THE POWER CONVERTERS FOR THE RF KLYSTRONS OF LEP

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ABSTRACT

The RF system of LEP required 100 kV power converters of about 4 MW continuous rating which could be fully controlled and short-circuited regularly on their output. Considerable time was invested in studies and the construction of a prototype converter in order to find the optimum topology to fulfil the RF requirements and which could be produced economically by European industry. A résumé is given of the studies carried out to achieve these aims with particular emphasis on primary thyristor control. The various choices are presented and the final chosen topology described. The protection and regulation systems are also discussed.

INTRODUCTION

At the beginning of the 1980s the RF group of LEP were finalizing their requirements for the klystrons. Although earlier thoughts had centred around a one klystron, one power converter scheme, the adoption of storage cavities to considerably reduce energy consumption meant that the klystrons would be operated in pairs. Hence one larger power converter could feed two klystrons thus giving an overall economy.

The specification required a voltage source, variable from 0-100 kV, capable of supplying continuously, up to 40 A. The impedance of the klystron loads would be non-linear and also variable. In order to limit energy deposited in the klystrons during arcing, a crowbar protection system would be used to short-circuit the high voltage. This would operate frequently, at least during conditioning and commissioning tests.

BASIC DESIGN CONSIDERATIONS

Many of the existing power converters for high power klystrons used roller-regulators to control the voltage and circuit-breakers to protect the units under short-circuit. While the roller-regulators gave good electrical performance they needed frequent maintenance and suffered considerably from the short-circuits. The circuit-breakers, because of the frequency of operation, degraded the reliability of the system and were generally slow to clear the faults (~100 ms). This put additional strain on all the components, and in particular the crowbar which had to sustain the short-circuit. It seemed that this approach could not be used for a 4 MW power converter.

For these reasons it was decided to consider a solid-state solution which would provide regulation and rapid protection at the same time. Thus the roller-regulator could be done away with and the circuit-breaker used for normal operation and as a back-up.

With a d.c. output power of 4 MW, about 5 to 6 MVA would be taken from the network and at such a level a twelve pulse system was obligatory. This would also reduce the output filtering needs and in particular reduce the size of the output capacitor thus minimizing stored energy and over-voltages. Four units would be used in each of the RF points of LEP and it was tempting to phase-shift them to get higher harmonic numbers. However since the operating levels of the various units would not be identical and thus harmonics might still add, this option was not taken up in order to simplify transformer design.

TOPOLOGY

Type of thyristor control

Having decided to use a solid-state solution the exact type of control and where it should be situated electrically in the converter had to be considered. The obvious control element at these powers was a thyristor and, although some thoughts were given to a resonant inverter as source, it was finally decided to use line-commutated phase controlled thyrisors.

Controlling the high-voltage output bridge was out of the question since a minimum of about 500 high-voltage thyristors would be needed per unit which could not be justified at only 40 A. In fact one small-current thyristor did exist on the market which could have done the job but the firing complications were still considerable. Since inversion was not an important requirement, this solution was abandoned and thoughts turned to primary control.

Two possibilities presented themselves: the units would be powered from the CERN 18 kV network and primary control could be envisaged at that level. Here the current was higher and the silicon would be better utilized than in the output. However it would still need about 200 thyristors to do the job. Such devices had been developed for reactive power compensation but they were still costly and complex. Further with only six command pulses, true 12 pulse operation could not be obtained throughout the operating range.

An intermediate voltage was therefore sought. The standard European level of 380 V was too low. Since a separate supply transformer would be needed, anyway per unit, it was decided to minimize the thyristor requirements. At that time a voltage line to line of 1000 V fulfilled this role and a transformer having six phases on its output could be used thus giving the possibility of true 12-pulse operation of the units. Hence a step-down transformer feeding a thyristor controller associated with a step-up transformer and diode bridge was chosen.

Thyristor/step-up transformer configuration

The prototype step-up transformer was delivered with an open delta primary and star secondary. Initial tests were carried out with the thyristors connected in the delta, known as a delta controller, as shown in Fig. 1.

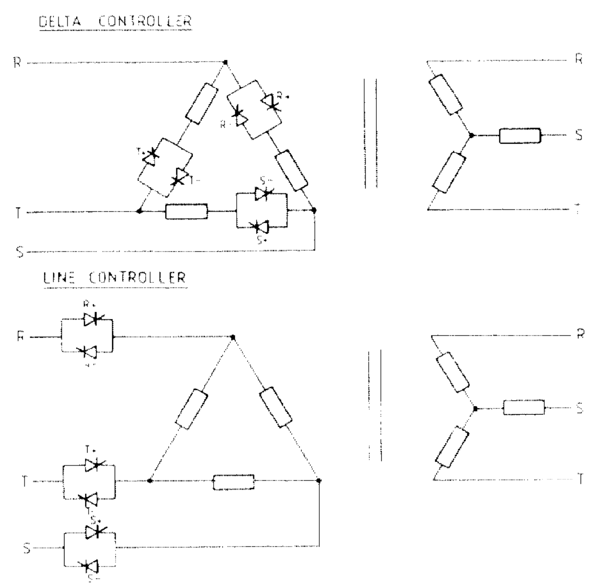


Fig. 1 Possible configurations of thyristor controllers

The theoretical turns ratio under closed delta operation is 27:1 but this rises to 40:1 under phase-delayed firing when one primary coil must supply the ampere-turn balance for two or three secondaries. This has two adverse effects on the transformer. Firstly the r.m.s current in the primary of the transformer for a given power throughput is increased and hence the power losses (Photo 1). Secondly the coupling is low and a large quantity of flux passes through the tank wall, once again increasing losses, this time to an unacceptable level. Although this system maximized on thyristor utilization, the transformer losses could be considerably reduced by reconfiguring to a line controller at the expense of increased current in the thyristor.

With a line controller the delta is always closed and the kVA is reduced to 0.74 of the previous value with an attendant form factor improvement from 1.6 to 1.06. The power dissipated in the thyristors increases by 1.79 but this is a much cheaper problem to solve than the previous one. The star secondary was maintained since it suited the high voltage application and a further effective kVA reduction is obtained in the secondary at certain operating levels[1]. A delta controller associated with a delta secondary does not suffer from the above mentioned problems.

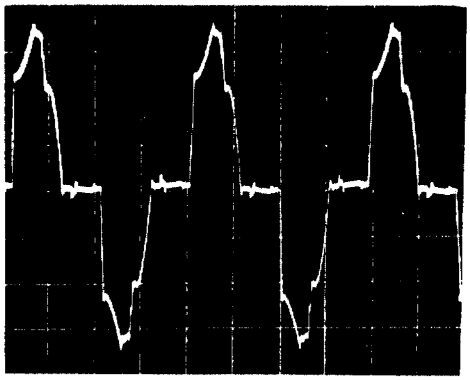


Photo 1a) Transformer coil current for delta controller (Irms=460 A -Output 100 kV/18 A)

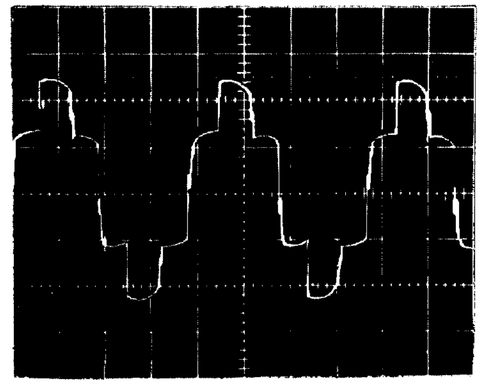


Photo 1b) Transformer coil current for line controller (Irms=340 A -Output 100 kV/18 A)

A second aspect with the line controller, which attracted us, was that it needed two control switches to fail for power to be fed to the load, unlike the delta controller where the failure of one meant a loss of control. This was an important aspect of the protection philosophy for the klystrons.

Hence a line controller feeding a delta/star transformer was adopted for LEP.

Parasitic oscillations

An earlier klystron test power converter had shown excessive parasitic oscillation after commutation, but the reason for this was never clear. The same was observed on the prototype converter and more detailed investigations were made. The parasitic oscillation is not detrimental to klystron operation but increases the suppression losses in the converter. The phenomenon can in fact be observed in all thyristor commutating equipment, it is however more pronounced with the high value of inductance of the output coils in the high-voltage transformers. These interact with the parasitic capacitance of the winding (and any other) to earth and act as a shorted pulse-forming network to earth with little damping at each thyristor firing. This results in an oscillating current passing through the earth system and the windings of the transformers. The simplest solution was to significantly increase the impedance to earth at the oscillary frequency, which was done by placing the main filter choke in the earth line. In the final LEP converters the output choke was split to give a symmetric arrangement and the parasitic capacitance to earth limited whenever economically possible (typically a few nanofarads).

Final configuration

The chosen topology is shown in Fig. 2

It consists of a transformer from 18 kV 3-phase to 1000 V 6-phase (delta/star), followed by two line commutated thyristor controllers and step-up transformer from 1000 V to 52 kV (delta/star). This feeds two full-wave diode bridges connected in series and a symmetric filter choke. The filter capacitor is located close to the klystron and crowbar.

Measurements were made to verify that the basic chosen topology and the thyristor firing system generated only high order harmonic currents in order to reduce the risk of internetwork oscillation and the amount of harmonic filtering necessary. At an output level of 100 kV/36 A, no measurable current below the 11th and 13th harmonic could be observed, the 11th being 2.2% of the fundamental and the 13th being 4.3%.

CONTROL AND PROTECTION

Firing circuits

The firing circuit for the above equipment needed the following particular characteristics:

- fast turn-off for incorporation in the protection scheme
- low or zero d.c. content in the voltage and current feeding the step-up transformer
- good twelve-pulse operation to minimize uncharacteristic harmonics.

A special circuit known as ASAD[2] was developed for this purpose. It is particularly suited to primary control since it is an open-loop firing system allowing a full set-up and test before power is used. It uses the same integrator on each of the pairs of thyristors in a line which assures the generation of respective pulses at exactly 180° spacing thus eliminating any d.c. component. It also incorporates a fast blocking and phase back input for the protection circuits.

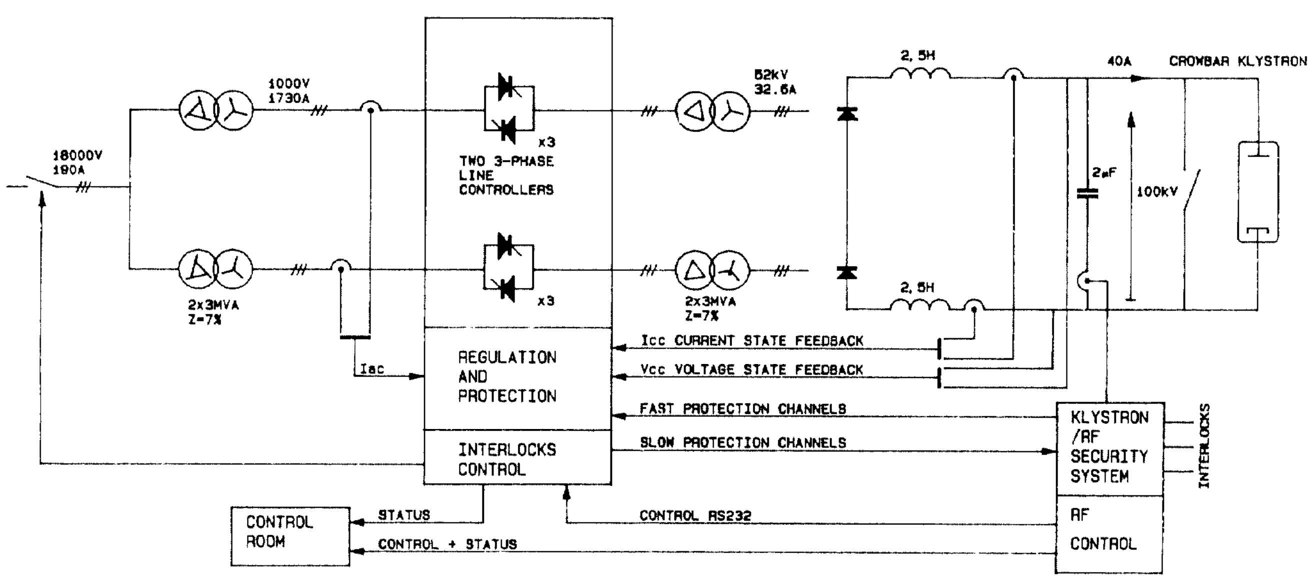


Fig. 2 Schematic of the 100 kV 40 A Klystron Power Converters

The blocking needs a special mention. Once a firing-pulse is initiated it is important to allow its completion even if a blocking signal arrives during this time. If not a thyristor may be partially fired and the current will not propagate across the entire silicon surface. This may result in thyristor failure particularly if a short-circuit is being applied. The ASAD firing circuit has such a facility.

Control loops

While the klystron can be represented by a resistance for small-signal analysis it is by no means linear, its resistance varying from 2.5 Ω to 25 kΩ . Since we want to create a voltage source at the output terminals we need a voltage loop around the filter. Its damping factor however is changed dramatically by the resistance of the klystron (from $\varepsilon = 0.32$ to $\varepsilon = 0.032$) thus making a classical compensated feedback difficult to optimize. State variable feedback was therefore proposed using the current in the choke to damp the filter via the thyristors. In this way a similar damped response can be obtained whatever the working point used by the klystron[3]. This is shown in schematic form in Fig. 2.

Protection

The power converters were designed to have the normal types of interlocks which will not be considered here. However the frequent short-circuits demanded not only a special construction to withstand the forces but also a rapid and reliable protection system to minimize their effect.

The crowbar is triggered by the rapid rise of current in the filter capacitor. At the same instance a signal is sent to the converter to block the thyristors. The a.c. current of the six-phases on the input to the line-controller is also monitored and used to block the thyristors as well. Should, after 20 milliseconds, the currents have not reduced to zero then as a backup the main circuit breaker is opened.

Several thousand crowbar short circuits were carried out in order to observe the reaction of the converter to such treatment and the response times. During these tests the longest observed current pulse was 7 milliseconds and the highest level was one-third the calculated worst case.

THYRISTORS UNDER CROWBAR

It was not clear, at the beginning, how well the thyristors would support the continual short-circuiting. With the help of the power semiconductor industry tests were made. At the inset of the short-circuit the thyristor junction might be operating near to its maximum temperature (125°C) and would therefore rise considerably above this level during the short-circuit. While it was generally accepted that a thyristor would survive occasionally such treatment, the long term effect was not so well understood.

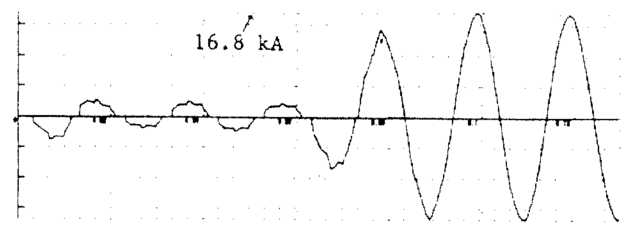
Thyristors suitable for our application needed a voltage grade of 3400 volts and would have a surge rating of about 25000 A. The peak half-wave current passing through the thyristor during a crowbar was calculated as 12000 A, and an instantaneous junction temperature of greater than 200°C was predicted.

Several manufacturers carried out tests for us, all fortunately with the same results and conclusions. After several thousand current pulses no degradation could be observed in the electrical characteristics of the thyristors. However on every occasion, when the thyristor/heat sink assembly was broken open after the tests, severe pitting was observed on the heat sink and device surfaces. This had also been seen on the prototype power converter but to a lesser extent. The air-cooled heat sinks were natural aluminium while the devices were tinned copper. The contact surface had a diameter of nearly 100 mm which meant that pressures were lower than normal. After experimenting with several types of pastes, contact washers and surface treatments the final solution was to plate both device and heat sink contact area with a 10 µmm layer of nickel. Todate we have seen no further evidence of this phenomenon.

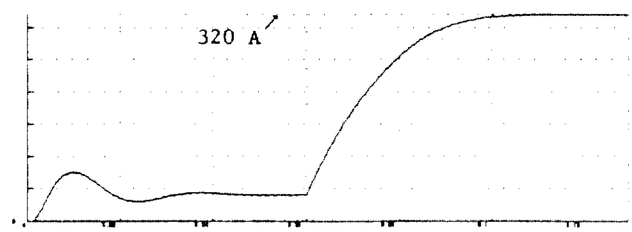
SIMULATION

The final topology was fed into the programme SCRIPT[4] so that a complete simulation could be carried out. While this confirmed the waveforms of the steady-state operation, it was invaluable in the evaluation of the fault conditions. The exact moment of the short-circuit could be chosen and the effects of many of the parasitic components could be included. In general the effect of the short-circuit was less severe than originally calculated and allowed a more realistic rating of the components thus avoiding any expensive overkills. The prototype confirmed these values.

Fig. 3 shows the current build-up in various part of the converter when the crowbar is fired. It should be noted that in normal operation the current will be stopped after the first half-cycle when the thyristor commutates off thus limiting fault currents to about one-third of their potential values. Equally the fault is removed within 20 milliseconds instead of 100 milliseconds in the case of circuit-breaker protection.



a) Current through a.c. controller



b) D.C. output current

Fig. 3 Simulation of start-up and short-circuit transient

CONSTRUCTIONAL DETAILS

The constructional details are covered in reference [5] which also deals with the testing and evaluation of the series production. It was decided to mount the diode bridges, filter chokes and other accessories in a separate oil tank for the following reasons:

- The more fragile elements could be contained together and in the case of a failure this unit alone could be replaced. Further the transformers would not be polluted or damaged by such a fault.
- The transformers could be run at higher oil temperatures and be purchased as individual units from non-specialized transformer manufacturers.
- Transport and handling problems were reduced.

CONCLUSIONS

Eight 100 kV, 40 A d.c. power converters are now in regular operation for the klystrons of LEP. They have proved extremely reliable and easy to operate. The chosen topology has fulfilled completely the specification, while the procurement in semi-kit form from non-specialist companies gave an extremely economic result.

Todate no maintenance has been necessary and the converters show every sign of giving many years of service.

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