IGBT INDUCTION-TYPE MODULATOR FOR X-BAND KLYSTRONS

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Abstract

A solid-state induction-type modulator was developed at KEK for the JLC project. The modulator consists of two oil-filled tanks; the first is for two klystrons and the second for a pulse transformer. The pulse transformer consists of 42 cores made from Finmet3 material. Each core is driven by a voltage of 3.2 kV by two IGBT plates; one of them has core reset circuits. The total number of IGBT plates is 84. The transformer has one turn at the primary and four turns for the secondary. This modulator can drive: pulse width up to 1.6 µs and high voltage up to a 500 kV pulse with a current of up to 540 A for two X-band klystrons. The pulse top flatness is 2%. The expected modulator efficiency is about 75%. We plan to test the modulator during the summer of 2005. We report here on the first status of this work, the result the core testing, the IGBT driver's electronics and protection system testing, and the result from the high voltage testing of some components of the modulator.

1 INTRODUCTION

Since the rf efficiency and stability strongly depend on the performance of the klystrons and modulators, intense studies have been conducted for their development. Various modulators were proposed for LC, and the induction-type modulator was a strong candidate modulator, which was possibly replaceable with a line-type modulator. SLAC had developed an induction-type modulator, and used it for the 8-pack module in NLCTA.[1] KEK also proposed the linear induction modulator (LIM), the concept of which was different from that of SLAC. The specifications of KEK's LIM are given in Table 1. Although KEK has been designing and manufacturing the LIM, after a decision of ITRP (International Technology Recommendation Panel) to choose the ILC accelerator technology over cold technology, the priority of LIM study became lower. In order to demonstrate the feasibility of LIM, a final test of LIM with a resistive load was performed. We obtained test results of 280 kV (max) with a pulse width of 1.1 µs, a repetition of 1Hz. The repetition was restricted by the power supply, which was not an essential matter. This report gives a general description and a test result of LIM.

Table 1 Technical Specification of Induction Modulator

Item	Unit	
Number of PPM Klystron		2 Klystrons
Klystron Voltage	kV	500
Total Current	A	540
Pulse width(70%-70%)	microsec	1.6
Pulse Top Flatness	%	2
Efficiency	%	65-85
Repitition Rate	Hz	100

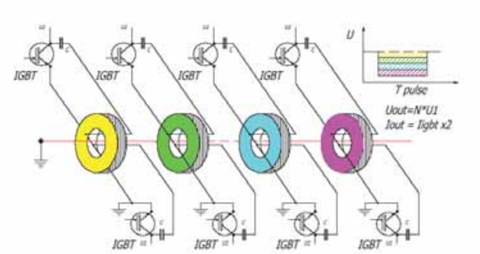

Fig. 1. Simplified concept of a linear induction-type modulator.

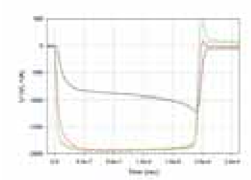

Fig. 2. Waveform of the IGBT test. A very fast rise time was achieved.

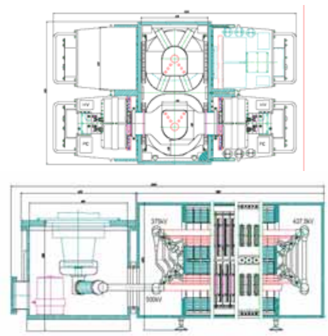

Fig. 3. Drawings of the LIM. Top is a cross section of the cores and the installed IGBT board. The bottom is the core assembly and the klystron load.

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[1] He is now in DESY, Germany.

2 PRINCIPLE AND STRUCTURE OF LIM

The principle of the LIM is simple, as shown in Fig. 1. If the number of the core is N, each current of the IGBT is $I_{IGBT,}$ and each IGBT commutates a voltage of U_1, the final voltage (U_{OUT}) is to be $N*U_1$ and a total current (I_{OUT}) is $I_{IGBT}*2$.

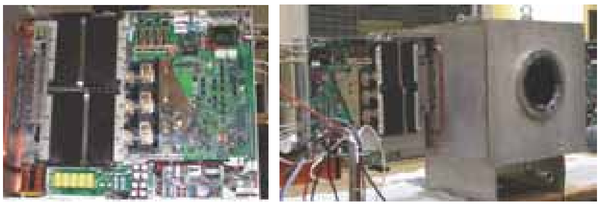

Fig. 4. IGBT plate (left) and installed boards for the 2-core setup test (right).

Although the principle is simple, there are several points to be carefully considered: IGBT protection, weight of the core material, the electrical field strength in oil, a switcher IGBT, the type of capacitors, and the system of modulator control and monitoring. In this modulator, the IGBT driver was specially designed to have a very fast rise time. Figure.2 shows the waveform of the test result. This is a special feature of this model. Variants for LIM for the JLC were considered at the first stage. Variants included a number of turns of the secondary winding, a 2-pack or a 4-pack for the klystron load, and the method of how to feed the power to the klystron (direct connection in the oil, cable connection, or coaxial line). Finally, a multi-turn induction modulator of the 2-pack type was adopted (four turns for the secondary winding were chosen). The pulse transformer consisted of 42 cores made from Finmet-3 material; each core was driven by a voltage of 3.2 kV by two IGBT plates, and one of them had core reset circuits. Therefore, the total number of IGBT plates was 84. In this case, a length of core was 2 m long and the weight of the cores was 1.4 tons, as shown in the drawing of Fig. 3.

For applying a high voltage, it was necessary to consider IGBT protection, the klystron's arcing detection, and the design of a 3.2kV feed-through from the plate to the core. The rise time and impulse flatness were also important issues. These are described later.

3 IGBT PLATE AND CONTROL SYSTEM

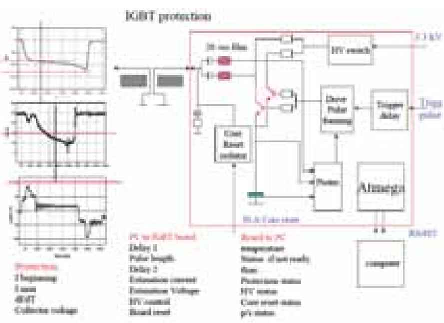

Fig. 5. Block diagram of the IGBT plate and the protection. scheme.

Eighty-four IGBT plates, each of which produced 3.2 kV, were carefully designed and all of them were tested before installing to the tank. Figure 4 shows pictures of IGBT plates. A block diagram of the IGBT plate is shown schematically in Fig. 5. This figure also shows the IGBT protection schemes. Each IGBT driver plate has a microcomputer, which is connected through the RS485 line to a local personal computer, and can be controlled. IGBT protection signals come from the following detectors: an over-current detector, an over-voltage detector, a dI/dt detector, a temperature detector, a reset current detector, a 20-micron thin iron fuse, and a gate driver with fast logic. Some of the protection schemes are shown in Fig. 5 along with the waveforms.

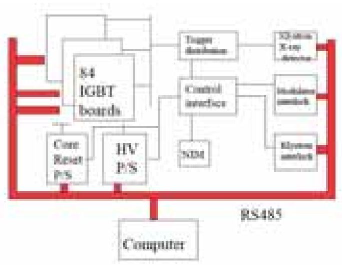

Fig. 6. Control systems.

Temperature information and the status, such as the protection status, HV status, core reset status and p/s status, are sent from the board to the pc if IGBT protection is not ready. The pc sends IGBT various signals related to a delay, the pulse length, estimated current and voltage, a HV control and a board reset.

For klystron arc protection, we prepared several counter measures, such as an additional inductance in an oil tank for each klystron, an X-ray detector,[2] fast logic in the gate driver and a current-limited circuit. These protections were achieved through the RS485 network with a pc, as shown in Fig. 6.

For the 3.2kV feedthrough from the IGBT plate to the tank, since there were no commercial ones available, we developed a special feedthrough comprised of a conductor plate molded with rubber packing, which sealed the insulation oil. The durability for 3.2 kV was tested, and the obtained results were good.

4 FABRICATION AND TESTING

Selection of the core material was an important issue for the LIM, since loss of the core was strongly related to the modulator efficiency and the total weight of the system. We compared the loss of various core materials, such as Finmet™, Metglas™, Amet™ and oriented silicon steel material. From the toroidal-core loss data (f=10kHz, B=0.1Tesla), Finmet was found to be less than 0.5W/kg and showed the nicest performance among them. We determined to use FInemet3™ as the core material for the pulse transformer. The performance of the first prototype of the Finmet cores was good for the acceptance test.

Before manufacturing the boards, a prototype model was tested in May, 2004 with the configuration of the 2-core setup having 4 IGBT plates, as shown in Fig. 4 (right). A high voltage was tested in the air, and we obtained a voltage of 6 kV and a current of 2 kA with a pulse width of 1.6 μsec and a repetition rate of 100 Hz. These results confirmed the design validity, and we started to manufacture all boards and cores.

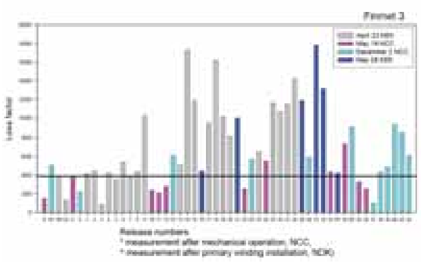

Fig. 7. Loss data of the Finmet3 core. The line shows the upper limit of the allowable loss.

During the manufacturing process, several problems were found: the surface insulation of Finmet was sometimes destroyed during the winding process of the foil, which led to a serious loss increase, as shown in Fig.7. The mechanical tolerances for the core were chosen to be high so as to make a tight contact with the conductor from the IGBT board: The architecture technology of installing the high-voltage parts on the print board was not performed well in the company product. Especially, the first problem was serious. For the second one, in order to make the core within the tolerance, the core manufacturer reformed the dimensions after epoxy-impregnation process, and the resulting core characteristics became poor. Figure 7 shows the fluctuation of the losses after core manufacturing. We should pay attention to the jig to prevent the cores from surface-insulation damage and from deformation during the epoxy-impregnation and drying process. Delaying the assembling and the ITRP choice forced us to reduce the activity for the LIM project. Finally, a test using a resistive load instead of using a klystron load was planned and performed in the summer of 2005.

Fig. 8. LIM assembly under testing.

Figure 8 shows the final assembly of LIM. Due to high tolerances between the pulse transformer assembly and the oil tank, insertion of the core assembly to the tank was not easy. The testing was limited to a lower repetition rate due to the rating of the resistive load and the power supply. We had prepared a power-supply of sufficient capability, while the remote control shown in Fig. 6 was not available in time. A test was performed with a power supply having a low-power capability of 3 kW, a repetition rate of 1Hz, a voltage of 280 kV (max) and pulse width of 1.1 μs. The limits came from the load.

A flat-top adjustment was also difficult since the fluctuation of the each core forced us to perform wider range tuning of each IGBT board adjustment than the original tuning range. Figure 9 shows the waveform of the output voltage from the LIM. In Fig. 9, three lines show the variation of the pulse top flatness by adjusting the timing and width of the IGBT driver. It is thus possible to obtain a flat top of the pulse within 2% after successive trials.

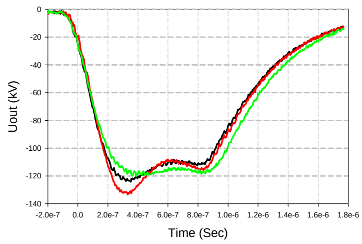

Fig. 9. Waveform of the LIM output pulse.

5 SUMMARY

We developed an IGBT induction-type modulator and performed the first successful tests up to 280 kV (max). This kind of modulator was thus proved to be operated in the rf source of a linear collider. We found several tasks to solve, such as the process control of manufacturing the Finmet core and a more flexible design considering the ease of maintenance. If these can be solved, the IGBT type modulator is promising for the future, by replacing the usual line-type pulse modulator.

6 ACKNOWLEDGEMENT

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