DESIGN AND CONSTRUCTION OF A LONG-PULSE MODULATOR

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Abstract

A long-pulse modulator for the 1-GeV proton linac planned at KEK was designed and constructed as a prototype and a component for testing developed klystrons and other power devices. The modulator is a standard line-type. The output pulse have a 15 MW peak power, 200 µs pulse width and 150 kW average power (600 µs and 450 kW are the final phase objective). Design parameters and operating characteristics will be discussed

Introduction

The 1-GeV proton linac for the Japanese Hadron Project[1,2], which is now under development at KEK, requires 36 L-band klystron amplifier stations in its high-β structure section. The klystrons will be operated at an unsaturated rf power of 4.0 MW, which corresponds to about 4.5 MW output power at saturated level. In order to achieve their reliable operation the power capability as high as possible is desired; we regard 6 MW output as the highest attainable power for operation of a 600 µs pulse width[3].

Performance of the modulators is a key point for successful operation of the rf system. We have decided to adopt a line type for the prototype modulator, judging mainly from a standpoint of having a great fund of operating experience. However, which type of modulators will be used for the 1-GeV linac is not yet decided.

Design Parameters and Circuit

A 6-MW klystron requires the modulator with a 15 MW pulsed power and a 140 kV high voltage, where the rf conversion efficiency and perveance are estimated to be 40% and 2×10^{-6} A/V$^{3/2}$, respectively. Taking account of characteristics of thyratrons used as switching devices, we determined the modulator output voltage to be 20 kV (PFN charging voltage of 40 kV)[4], so that a step-up ratio of a pulse transformer is 7:1. The average power output is 450 kW at the 600 µs pulse width and 50 Hz repetition rate. These design values required for the prototype modulator is summarized in table 1. In a line-type modulator an increase in the pulse width makes the size of the PFN larger, and a very high duty factor makes it difficult to perform reliable operation. Thus, in the first stage of construction the output pulse width was decreased to 200 µs, especially to save the initial investment. However, all the other components such as an IVR, transformers and diodes are fabricated so as to have capability of full rating operation.

Table 1 Basic Parameters of the prototype modulator (Symbol * indicates the final objective.)

Peak power	15 MW	
Average power	150 kW	(*450 kW)
Pulse voltage	20 kV	
Pulse current	750 A	
Pulse width	200 µs	(*600 µs)
Pulse rise time	< 20 µs	
Pulse repetition rate	50 pps	

A simplified diagram of the designed modulator is shown in Fig. 1. It consists of a high voltage dc power supply, charging circuit, PFN and discharge circuit. A crowbar is incorporated in the output circuit to protect the load in the event of fault. The output pulse width will be increased up to 600 µs by adding the PFN and main thyratron by two steps (phases 2 and 3). Two thyratrons will be connected in parallel for operation of a 600 µs pulse width.

High Voltage DC power Supply and Charging Circuit

The high voltage dc power supply consists of an induction voltage regulator (IVR), two rectifier transformers connected in series, a filter inductor and a capacitor bank. The power supply provides an average power of 500 kW at 22.5 kV. By connecting the two rectifier transformers so that one is in a delta-

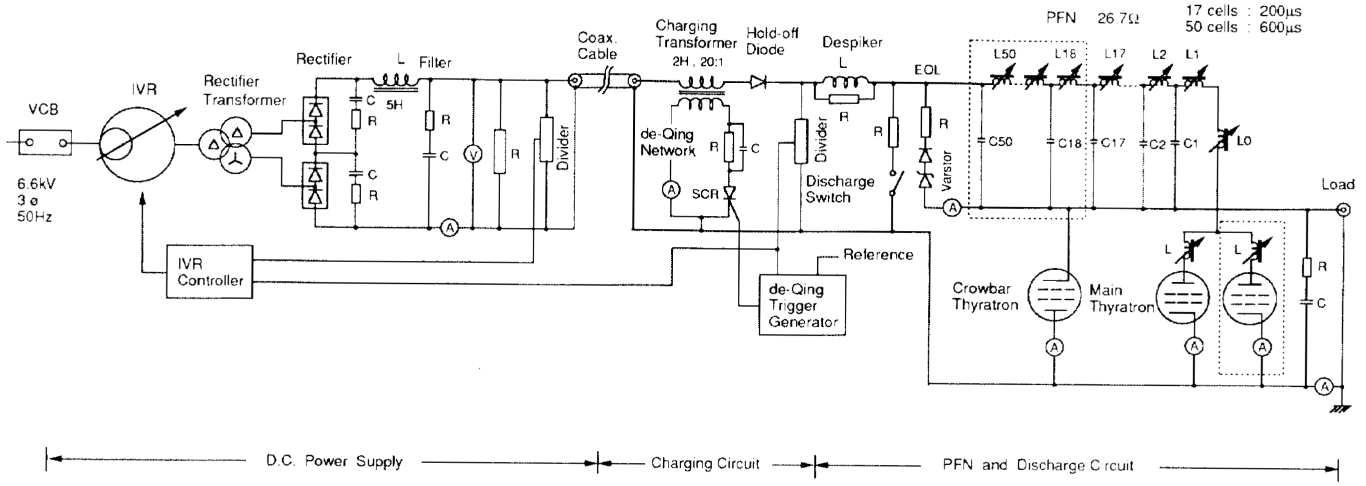

Fig. 1 Simplified circuit of the prototype modulator. Dashed boxes indicate components added at the final phase.

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delta configuration and the other a delta-wye configuration, 12-phase ripple is produced, and the required voltage drop in a charging voltage regulator (de-Q'ing circuit) is reduced. A shorted current in the event of a main thyratron fault or arcing in any of high voltage circuits is limited to no more than 10 times the normal full load current by the IVR and transformer reactances of 10 %. The output voltage is continuously variable from 40 % to 100 % by the IVR. The driver signals to the IVR are provided from its control unit, which maintains the dc output to be slightly higher (3 %) than half of the charging voltage on the PFN.

The charging voltage to the PFN is regulated by the de-Q'ing circuit in the secondary of the charging transformers, which have a 1:20 step-down ratio to allow use of SCR's as a switching device. This technique had been developed at SLAC. The de-Q'ing circuit in this modulator is normally adjusted to dissipate 3 % of the PFN voltage in the load resistor, which is installed in an oil tank. The dissipated power of 25 kW maximum is cooled by water.

The charging time is determined by a primary inductance of the charging transformer and the total PFN capacitance. In the case of a 200 µs PFN, the charging time is 8.7 ms (as shown in Fig. 2), and becomes 15 ms for a 600 µs PFN. The time constant of the de-Q'ing current is reduced by connecting a capacitor in parallel with the de-Q'ing resistor, because the resistance, which is required to cut off sharply the charging current to the PFN, is very low (3 Ω), so that the decay time becomes very long. The waveform of the de-Q'ing current is shown in Fig. 3.

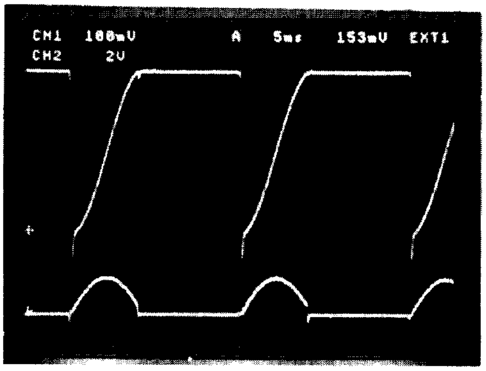

Fig. 2 Charging voltage and current of the charging circuit (Vertical scale, upper trace 10 kV/div lower trace 33.3 A/div and horizontal scale 5 ms/div).

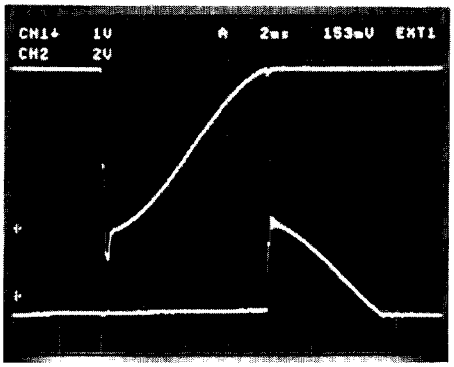

Fig. 3 Charging voltage and de-Q'ing current (Vertical scale, upper trace 10 kV/div, lower trace 80 A/div and horizontal scale 2 ms/div).

Pulse Forming Network (PFN)

The designed values of the PFN were based on the final objective of a pulse width of 600 µs and an average power of 450 kW at 50 pps. Taking into account the cabinet size, space factor and cooling for PFN components, we determined the parameters for a 200 µs pulse width (table 2). The 26.7 ohm PFN consists of 17 cells; each cell having a 160 µH inductance and a 0.22 µF capacitance. One cell capacitor is divided into four ones connected in parallel in order to increase radiation surfaces, which are cooled by forced air. This capacitor has a paper/polypropylen mixture as dielectric and is impregnated with mineral oil. The working voltage is 45 kV and the tan δ less than 0.5 %.

Table 2 Design parameters of the PFN
(Symbol * indicates the final objective.)

Number of cells	17	(*50)
Pulse width	200 µs	(*600 µs)
Impedance	26.7 Ω	
Charging voltage	40 kV	
Pulse current	750 A	
Flat top ripple	< 0.5 %	
Inductance/cell	160 µH	
Capacitance/cell	0.22 µF	

Since the inductance of each cell is relatively large, the inductor uses an iron core, which is laminated by a thin iron sheet of 0.1 mm thick to reduce the temperature rise due to eddy current loss. To minimize the flat top ripple and to compensate the pulse transformer sag, the inductance is variable in a range of ± 20 %. This is realized by varying air gap spacing in the core, and is adjustable even under high voltage operation conditions. A cross section of the iron core is made relatively large to prevent it from saturation even for the case of a shorted load. By keeping the PFN impedance constant, it is possible that the shorted current through the load and PFN does not exceed two times that of the normal load. The inductors are thus made so as to maintain an inductance of more than 70 % of the normal case at 200 % over current.

The inductance of the first cell is increased by a factor of 2 or 3 to suppress oscillations superimposed on the flat top of the pulse. The end of line clipper is used to absorb the negative voltage reflected from the low impedance or shorted load, and prevents over charging or de-Q'ing in the next charging cycle.

Switching Devices

We determined for the time being to use thyratrons as main and crowbar switching devices of the prototype modulator. After completion of evaluation of this prototype, we are planning to replace it by solid sate devices such as a SCR and GTO (gate turn-off SCR).

Because the ITT F-175 (or kV-275C) thyratrons have been successfully operated at the 2.5-GeV electron linac (rated at 45 kV, 3000 A and 3.5 µs) and the 40-MeV proton linac (rated at 20 kV, 500 A and 280 µs) in KEK, we first used these tubes in parallel as the main switch at 40 kV, 750 A, 200 µs and 7.5 A average. However, after initial tests, we had to conclude that the F-175 thyratrons could not withstand the charging voltage above 30 kV under long pulse and high duty conditions. Thus these have been replaced by the ITT F-259 thyratron, which was recently developed for very high duty operation (50 kV, 10 kA peak and 25 A average) by ITT. Meanwhile, the crowbar thyratron is not operated at high duty and high current, so that the F-175 is still used.

This crowbar circuit equipped in this modulator have two functions; one is an ordinary function to protect extreme damage in shorted loads by shorting the output current, and the other is to ensure extinguishing main thyratron fire until the next charging start. When the modulator is operated for a klystron load at low rating power, a positive mismatch would occur usually and the positive voltage would be applied to the thyratron anode during more than twice the output pulse width, resulting in continuous conduction of the thyratron. To avoid this failure, a crowbar thyratron, or clip tube is used to short this positive voltage tail to ground by proper timing of its firing (Fig. 4)

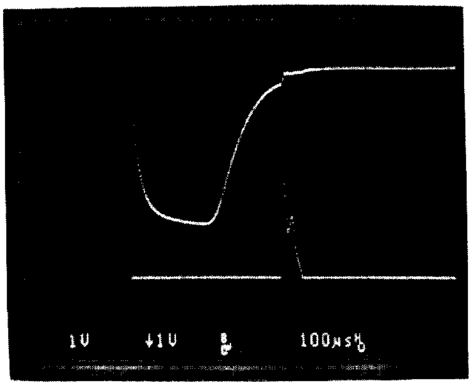

Fig. 4 Modulator output voltage without adjustment of the PFN inductors and crowbar thyratron cathode current at a klystron load with a pulse transformer (Vertical scale, upper trace 5 kV/div, lower trace 20 A/div and horizontal scale 100 μs/div).

To operate reliably two main thyratrons in parallel, it is necessary to take balance of each tube current. To accomplish this requirement a variable inductor having an inductance of 320 μH maximum will be incorporated in the anode circuit of the individual thyratron for 600 μs pulse width operation. The F-259 thyratron requires dielectric liquid immersion for operation in excess of 35 kV, and thus installed in an oil tank with natural air cooling radiators (Fig. 5).

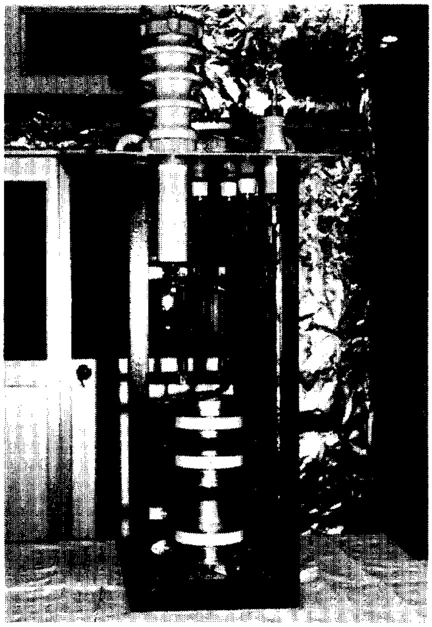

Fig. 5 F-259 thyratron suspended from the oil tank lid.

Test Operation and Experience

Test operation of this modulator with a resistive load (unfortunately, having excessive inductance) have been done for about six months at KEK. The most serious problem occurred shortly after the initial test and was associated with the failure of the main thyratron F-175's, designed for short pulse appreciations. After several attempts, these were replaced by the ITT F-259 thyratron, newly designed for high duty and high average current use. Owing to this tube the modulator have accomplished the designed objective; 40 kV charging voltage, 200 μs pulse width and 50 pulses per second rate. In the first test, the inductors equipped to balance the paralleled thyratrons have been proven available for equalizing the individual cathode currents. However, it seems that the clipping function of the crowbar thyratron to avoid main thyratron continuous conduction is not necessary for operation of a 200 μs pulse width. This modulator is now used to test a klystron (Thomson TH2104 A; rf output power of 5 M peak, 150 kW average) without major problem.

Overview of the modulator and the klystron mounted on the pulse transformer tank.

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