LONG-PULSE MODULATOR DEVELOPMENT FOR THE SUPERCONDUCTING RF TEST FACILITY (STF) AT KEK

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Abstract

This paper describes a long-pulse 1.3 GHz klystron modulator that was developed for the Superconducting RF Test Facility (STF) at High Energy Accelerator Research Organization (KEK). The modulators is a direct-switched-type design with a 1:15 step-up transformer and a bouncer circuit to compensate for the output pulse droop within ±0.25%; it can drive a klystron with up to 10 MW peak power, 1.5 ms rf pulse width, and up to 5 pps repetition rate. The main features of this modulator are the use of four 50 kW switching power supplies in parallel to charge the storage capacitors to 10 kV, self-healing-type capacitor to realize a compact storage capacitor bank, and a highly reliable IGBT switch which enables elimination of a crowbar circuit. Design considerations and its performance are presented. An IEGT(Injection Enhanced Gate Transistor) switch composed of six series devices, each having a rating of 4.5 kV and 2100 A-DC, has been also developed to realize a compact and high-reliable modulator.

INTRODUCTION

The Superconducting rf Test Facility (STF) is a project at KEK for building and operating a test linac with high-gradient superconducting cavities as a prototype for the main linac systems of the International Linear Collider (ILC). The STF has been under construction since 2005 and the plan includes phases 1 and 2. Phase 1 was completed in 2008 and phase 2 is ongoing [1].

Two modulators have already been built to drive the klystrons for the STF. One new modulator is being built. These modulators are a bouncer-type design that is considered the baseline design for the ILC klystron modulator [2]. In 2005, the first modulator was built by converting from an old klystron modulator system in order to rapidly start up the project. This modulator has a 1:6 step-up transformer and an IGBT switch, and can drive a klystron with up to 3.9 MW peak power [3]. The second modulator, which is capable of driving a 10 MW klystron, was designed and built aiming for a compact, low-cost and high-reliable modulator in 2007. While, an IEGT switch was also developed to realize a compact and high-reliable switch. In the third new modulator, this IEGT switch is used in place of IGBT. This paper will focus on the second modulator.

KLYSTRONS

Two types of klystrons will be used as rf sources in the STF. One is a 5 MW conventional single-beam THALES TH2104 klystron. The other is a 10 MW multi-beam E3736 klystron developed by Toshiba Co. for TESLA. Table 1 lists the specifications of these klystrons.

Table 1: Klystron Specifications

Klystron	**TH2104**	**E3736**
Operating frequency (GHz)	1.3	1.3
Rf pulse width (ms)	1.5	1.5
Peak output power (MW)	5	10
Beam voltage (kV)	130	120
Beam current(A)	92	140
Microperveance	2.0	3.4
Number of beams	1	6
Efficiency(%)	42	60

SECOND MODULATOR

The second modulator has been designed to drive a 10-MW multi-beam klystron as well as a 5-MW single-beam klystron. The specifications and requirements of the modulator for the E3736 klystron are summarized in Table 2. Figure 1 shows a simplified circuit diagram of the modulator. The modulator comprises of four switching power supplies, a storage capacitor bank, a series IGBT switch, a bouncer circuit and pulse transformer. The details are described in the following subsections. We eliminate a crowbar circuit by reinforcing the IGBT switch protection. The transformer ratio is chosen to be 1:15 to use a more compact series IEGT switch in the future, which improves both the switch reliability and modulator size. There is changed from the Basic Configuration Design value 1:12. The switching power supplies and self-healing-type capacitor contribute to the compact size of the modulator.

Table 2: Specifications of STF modulator#2

Peak output power	16.8 MW
Secondary output pulse voltage	120 kV
Secondary output pulse current	140 A
Pulse flat-top	1.5 ms
Rise time	< 0.2 ms
Pulse width	1.7 ms
Transformer ratio	1:15
Pulse flatness during flat top	< ±0.5%
Energy deposit in klystron from gun spark	< 20 J
Repetition rate	5 pps

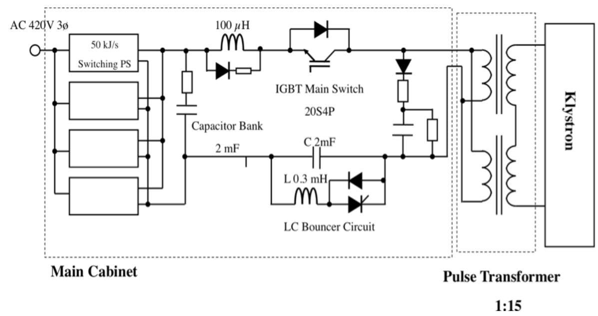

Figure 1: Simplified circuit diagram of STF modulator #2.

Figure 2 shows the main modulator cabinet and the pulse transformer tank on the right side. The size of the main cabinet is 4.2 m (width) × 2.2 m (depth) × 2.2m (height).

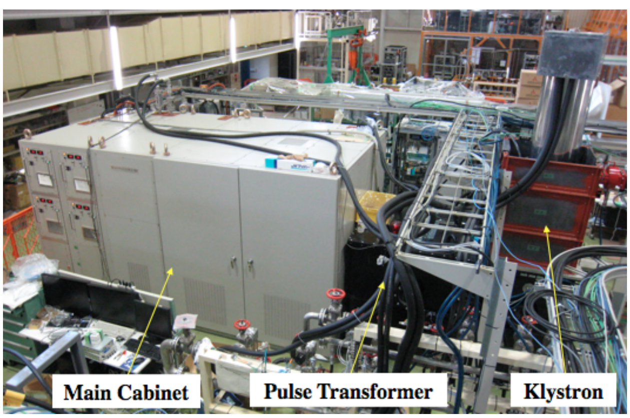

Figure 2: Overview of STF modulator #2.

Switching Power Supply

Four 50 kW switching power supplies are used in parallel to charge the storage capacitors with a total capacitance of 2 mF to 10 kV at 200 kJ/s. The supplies are based on an IGBT-switched 20-kHz inverter and have a voltage regulation of less than ±0.5% at 5 pps operation. The supplies are fed with a three phase ac voltage of 420 V and they are water cooled.

Self-healing Capacitor

In order to realize a very compact capacitor bank, we used self-healing (SH) capacitors developed by Nichicon. They comprise polypropylene films coated with thin aluminum electrodes, which form a small segmented metallization pattern to prevent a catastrophic failure that may arise from an internal high-energy discharge. This dielectric system enables the dielectric strength to be increased to up to 300 V/μm for an operational lifetime of 100,000 hours at 5 pps.

The capacitor bank uses four SH capacitors in parallel. Each capacitor is a bushing style metal box with a capacitance of 500 μF and a size of 68 cm (width) × 25 cm (depth) × 65 cm (height). The energy density of the capacitor is 270 kJ/m^3.

Bouncer Circuit

The pulse droop of 20% that is produced by the discharge of the capacitor bank is compensated by the use of a low impedance resonant LC bouncer circuit developed by FNAL. In order to optimize the L and C parameters for pulse flatness, we have simulated the output waveform using the Micro-Cap program. From the simulation results, L and C were determined to be 0.3 mH and 2 mF, respectively.

IGBT Switch

The IGBT switch comprises 20 units in series(Arm) and 4 units in parallel, total 80 units to operate at a voltage of 9 kV and switch 2100 A both on and off for the E3736 klystron. Each unit has an IGBT(Mitsubishi CM600H-24H) device having a maximum voltage rating of 1200 V and an average current rating of 600 A, which is the same as the device used in the first modulator because of its proven reliability and low-cost. Each unit is also equipped with a sunbber circuit, a gate drive circuit and monitor circuit for detecting the short-circuiting of the device. In the snubber circuit, an RC network and ZNR are connected to the device to meet the required turned-off voltage during klystron arcs. The gate signals are fed through an optical fibre cable. The monitor circuit measures each device voltage; a device is decided to have shorted if its voltage is less than 50 V when the switch turns off. In such situations, the switch is rapidly stopped in order to protect it. In order to simplify the switch system, the dc power for the gate drive circuit is fed through the main circuit. There are six current detectors in each Arm, the primary and secondary lines of the pulse transformer. They are used for fast over-current protection of the IGBT switch to obtain high-reliability.

Pulse Transformer

The pulse transformer is divided into two step-up transformers to reduce the volume of an oil tank and leakage inductance. One is for full withstanding voltage and the other for half withstanding voltage. They have laminated cores, which made of 0.3 mm thick silicon steal plates, and connected parallel to the primary winding and series to the secondary winding. The primary inductance, leakage inductance, and stray capacitance in the secondary side are estimated to be 92 H, 36 mH and 844 pF, respectively. The pulse transformer is housed in the oil tank with a heater isolation transformer and a dc bias transformer. The klystron is also placed on the tank vertically. The size of the tank is 2.2 m (width) × 1.1 m (depth) × 1.4 m (height). The total weight including the oil is 8.3 tons.

Performance Tests

Figure 3 shows the klystron(TH2104) voltage and current waveforms as well as the output rf power waveform at a repetition rate of 5 pps and a charging voltage of 9.6 kV. Pulses with a peak voltage of 127 kV, peak of current of 85.5 A, width of 1.7 ms, rise time of 92μs (10–90%), and flat-top width of 1.5 ms within 0.47% (peak-to-peak) were successfully generated and the output rf power then reached 5 MW.

Figure 4 shows the klystron voltage and current waveforms during a klystron gun spark at a charging voltage of 9.0 kV. Assuming the arc voltage to be 100 V constantly, energy deposit in klystron from gun spark is 2.0 J. This value meets the modulator requirements.

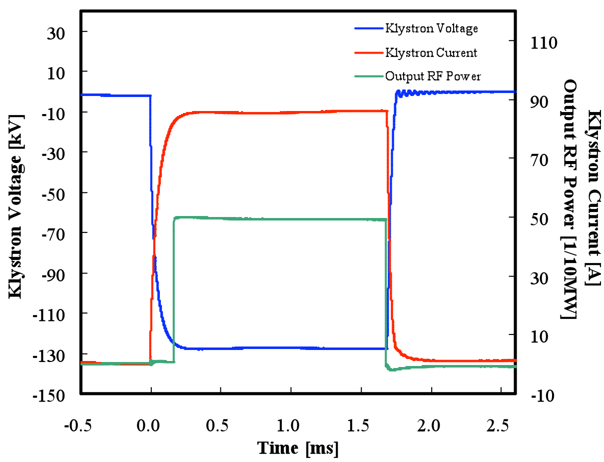

Figure 3: Klystron voltage, current and output rf power waveforms.

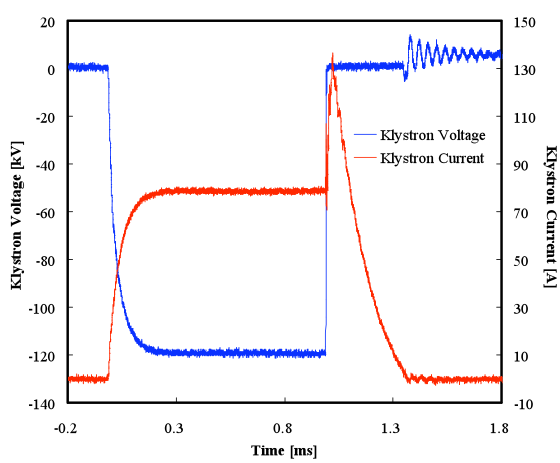

Figure 4: Klystron voltage and current waveforms during a gun spark.

IEGT SWITCH DEVELOPMENT

An IEGT switch composed of six series devices has been developed to realize a compact and high-reliable modulator [4]. Figure 5 shows overview of the IEGT switch. The IEGT device has a maximum voltage rating of 4.5 kV, an average current rating of 2.1 kA and a peak current rating of 4.2 kA. It is the largest commercially available semi-conductor device at this time. The switch can turn off large current with small snubber capacitance of 3.5 μF because of its low inductance structure. In order to improve reliability for the short circuit fault of the IEGT device, the switch has redundancy of one device and is equipped with a detector of short circuit fault for each IEGT device. This switch is used as a main switch for the third modulator.

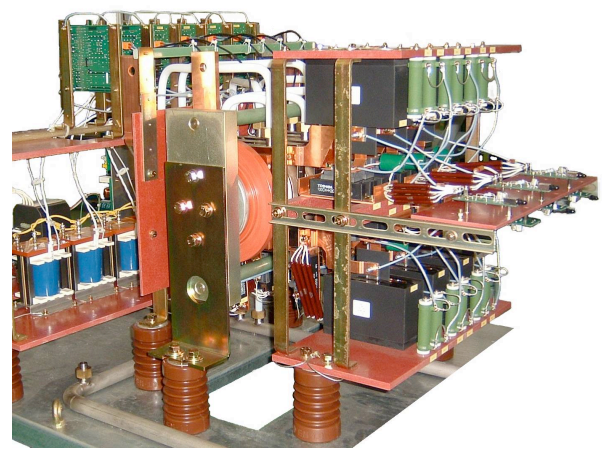

Figure 5: IEGT switch assembly.

SUMMARY

The second modulator for the STF has been completed. In the performance tests on the klystron, a pulse with a peak voltage of 127 kV, peak of current of 85.5 A, pulse width of 1.7 ms, rise time of 92 μs (10–90%), and flat-top width of 1.5 ms within 0.47% (peak-to-peak) were successfully generated at 5 pps and the output rf power then reached 5 MW. This modulator is used for a high power test of the coupler for the cavity. The third new modulator with an IEGT switch is under construction.

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