DEVELOPMENT OF HIGH-POWER HIGH-VOLTAGE DC POWER SUPPLY BASED ON SERIES RESONANT TECHNOLOGY FOR MW CLASS RF AMPLIFIER

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Abstract

High-power high-voltage dc power supply has been developed based on series resonant converter technology for a MW class RF amplifier. For low-voltage ripple, an IGBT inverter consisting of 1400 V-600 A devices is drives with a maximum switching frequency of 31.2 kHz.

A performance test was carried out using an RF amplifier. We examined this power supply under two different conditions. One was with a voltage of 10 kV under a 1-sec rectangular-wave output current. The voltage ripple was 21 V_{PP} with a peak current output of 92 A. The other was with the same voltage under a 24-msec half-sine wave output current. The voltage deviation was 150 V_{PP} during the 24-msec half-sine wave output.

A protection test for a short circuit in the RF amplifier was also examined. The test wire was not fuse. Therefore it was proved that this dc power supply can protect RF amplifier from a short circuit fault without a crowbar circuit.

These experiments showed that the dc power supply had a low voltage ripple and high-speed response, thus verifying that it performed well for the MW class RF amplifier.

INTRODUCTION

In Japan KEK and JAERI are proceeding with a joint project to produce a high-intensity Proton synchrotron accelerator. The synchrotron requires a MW class RF amplifier to accelerate a proton beam. The anode dc power supply for this amplifier required high power, high voltage and high stability. In addition, this power supply needed small voltage ripple, which affects the proton beam, and a constant voltage, which is made under high-speed response with changes of output current.

For a conventional anode dc power supply for an RF amplifier based on thyristor converter technology, a large capacitance dc filter is necessary to reduce the voltage ripple caused by the convert utility voltage (50/60Hz), therefore the energy into an RF amplifier is large in case of a short circuit fault. As a result, a protection circuit so called "crowbar" circuit has been indispensable for conventional thyristor power supply systems.

To solve the above problems, we have developed a high-power dc power supply for an RF amplifier based on series resonant converter technology. With this technology, switching frequency can be made quite high. As a result, dc filter capacitance can be reduced. The dc power supply has three advantages for a high-power RF amplifier.

First, the voltage ripple, which affects the proton beam, is small. Second, the change of output current in a rapid cycle, the voltage deviation is small. Third, no crowbar circuit exists.

This paper describes the design and the experimental investigation of the power supply.

DESIGN OF DC POWER SUPPLY

1) Specification

The dc power supply based on series resonant technology is specified in Table 1. Figure1 shows a block diagram of the dc power supply system. The system consists of an input circuit that contains a utility transformer and rectifier converter, a main circuit and a controller. The main circuit includes fifteen inverter units and a H.V. output section.

Table 1:Specifications of the dc power supply

Item	Specification
Output voltage	10 kV (maximum 13kV)
Output current	92 A
Output power	peak 1.2MW (duty 60%)
Efficiency	> 80 %
Voltage ripple rate	< 0.2 $\%_{0\text{-}P}$ (@10 kV)
Voltage deviation	< 1.0$\%_{0\text{-}P}$ (@24-msec half-sine wave output current)
Energy poured into tube in case of short circuit fault	< 50 J

2) Dc input circuit

The dc power supply requires a dc input voltage of about 700 V, from the utility voltage stepped down through a 1.7 MW transformer (6.6 kV/505 V) and converted to dc voltage by a 12 pulse-rectifier converter, which were put in an outside oil tank.

3) Inverter unit

The IGBT inverter consists of four arms and each arm consists of two paralleled IGBT devices. Thay are 1400 V-600 A devices. They are provided with built-in free wheel diodes (FWD) to carry reverse current. The switching frequency is 31.2 kHz maximum. The inverter is designed to operate under zero current switching mode, where the IGBTs turned off while reverse current is flowing through the FWD in order to minimize switching losses at turn-off period. The snubber circuit could be

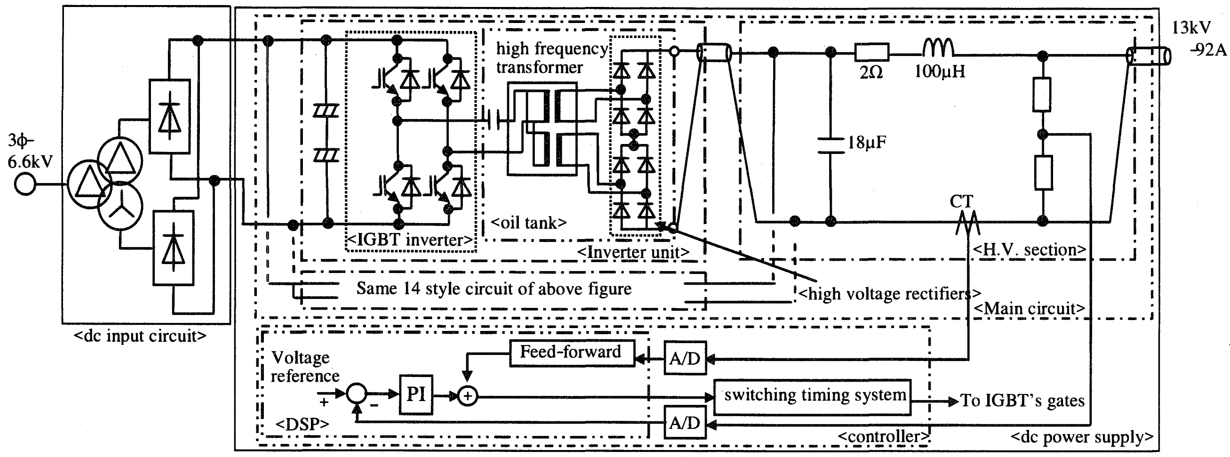

Figure 1 Schematic diagram of dc power supply for high power RF amplifier

removed since the IGBT's over voltage at turn-off does not arise.

The resonant circuit consists of 1.5 μF resonant capacitance and the total circuit inductance that consists of a bus inductance and a leakage inductance of the high frequency transformer. In order to maintain the zero current switching (ZCS) condition under the high frequency operation of IGBT, the leakage inductance of the high frequency transformer must be low. This transformer is composed of two units. In each unit, the secondary winding is wound between two primary windings to obtain a high coupling factor between the two windings and to minimize leakage inductance.

Secondary winding is connected to high voltage full bridge diode rectifiers, which are connected in series. These rectifiers consist of twenty diode devices in series. They are 1000 V-20 A devices with the specification of ultra fast recovery to reduce recovery loss.

Figure 2 shows an external view of the inverter unit. The resonant circuit and high voltage rectifiers are installed in an oil tank for cooling and insulation.

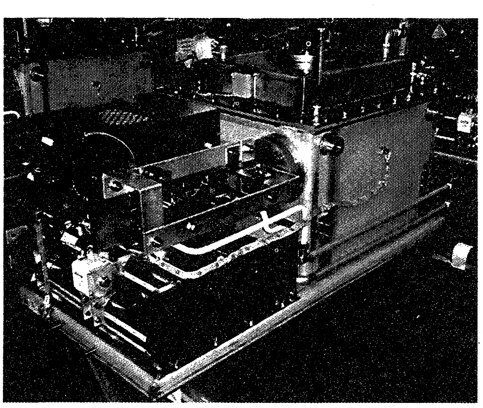

Figure2 External view of invert unit

4) H.V. Output section

At the H.V. output section, the filter capacitance of 18μF is charged by the resonant currents, outputting from 15 inverter units. Because 15 inverter units are multiple connected and operated with equivalent frequency of 468 kHz (= 15*31.2 kHz), the filter capacitance is reduced by about 1/10 compared to the conventional dc power supply. Therefore the energy that pours into a load in case of a short circuit fault reduces dramatically. Then a crowbar circuit can be removed. A resistance of 2 ohm is connected in series at the output circuit because most of capacitance energy is consumed when a short circuit fault occurs. Moreover, connecting a 100 μH air core coil in series is aimed at both decreasing peak current of a short circuit and choking for voltage ripple.

5) Controller

The controller quickly maintains the output voltage collect by changing the IGBT switching interval. The output voltage is detected by the voltage divider at the H.V. section and is kept constantly by the feedback control system. Furthermore, feed-forward control maintains the output voltage at a constant value against a sudden change of the load current. The feed-forward control detects the output current and converts it directly the IGBT switching interval.

Figure3 shows an external view of the dc power supply's main circuit. It's dimensions of were 4500mm(W) x 2000mm(D) x 2650mm(H).

EXPERIMENTAL RESULT

The performance test was carried out on the dc power supply with a high power RF amplifier that was able to output 1MW to drive tetrode tubes (TH588) by push-pull. Figure 4 shows a schematic diagram of the test circuit. The 100 m coaxial cable was connected between the dc power supply output and the anode of the tubes. By changing the control grid level, the RF amplifier output power was changed. Output voltage of the dc power supply was measured at the end of the coaxial cable, and the output current was measured at the cathode of the tubes in the RF amplifier with shunt resistance.

The performance of dc power supply was confirmed with three kind of test. Firstly, voltage ripple was evaluated under 1-sec rectangular wave output current at 10kV. Secondly, voltage deviation was evaluated under 24-msec half-sine wave output current at 10kV. Lastly, protection test against a short circuit was carried out.

Figure 5 shows the output voltage waveforms when the output current was a 1-sec rectangular wave. The current changed repeatedly from 5 A at the bottom to 92 A at the peak. The voltage deviation was 600 V when changing from 5 A to 92 A. The ripple voltage was $21V_{pp}$ ($0.1\%_{0\text{-}p}$) for 92 A.

Figure 6 shows the output voltage waveform when the output current was a 24-msec half-sine wave. The peak current was 92 A while the idling current was 5 A. The voltage deviation was 150 V_{pp} ($0.75\%_{0\text{-}p}$) in the 24-msec half-sine wave output.

The protection test for a short circuit fault inside the RF amplifier was performed with 100m coaxial cable. A short gap and a test wire (ϕ=0.3mm, L=200mm) were connected in series at the end of the coaxial cable. This test was carried out at the highest voltages in our operation: 13kV. Figure 7 shows the voltage and current waveforms in this test. The test wire did not fuse, because a resistance of 2 ohm in the dc power supply consumed the most of its energy storing the dc filter capacitance.

From the results of above three tests, it was confirmed that the power supply has satisfied the specification in Table 1.

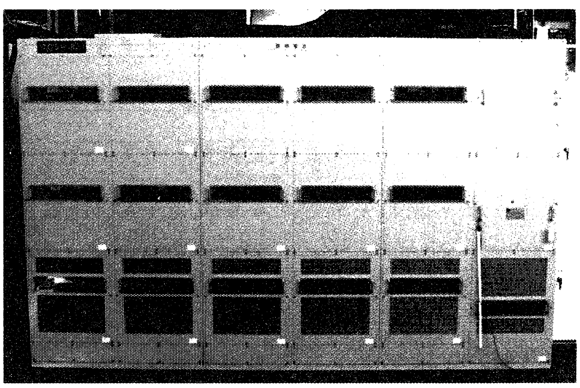

Figure 3 External view of dc power supply main circuit

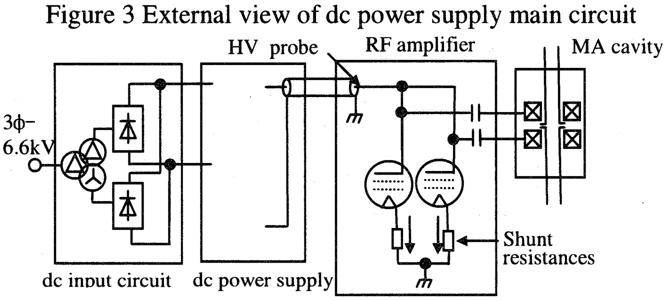

Figure4 Schematic diagram of performance test circuit

CONCLUSION

A high-power, high-voltage dc power supply has been developed utilizing series resonant converter technology for a MW class RF amplifier. The dc power supply has been shown the excellent performance of low-voltage ripple and high-speed voltage control. The low-voltage ripple performance has been attained by 15 inverter units which are multiple connected and operated with equivalent frequency of 468 kHz.

Moreover, the voltage control system which varies the switching interval corresponding to the load current has exhibited high accurate voltage stability against the rapid change of the output current.

A protection test against a short circuit was also examined. The test wire was not fuse. Therefore it was proved that this dc power supply can protect RF amplifier from a short circuit fault without a crowbar circuit.

The experiment showed that the dc power supply had good performance for a MW class amplifier.

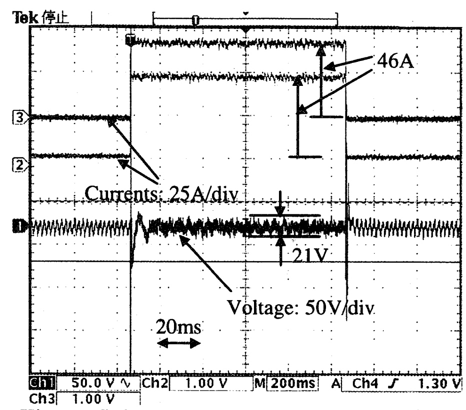

Figure 5 Output voltage under 1 sec rectangular wave output current.

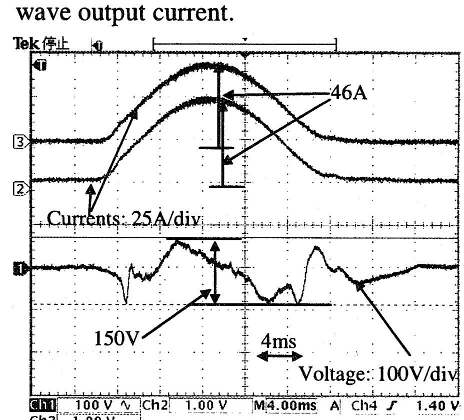

Figure 6 Output voltage under 24-msec half-sine wave output current.

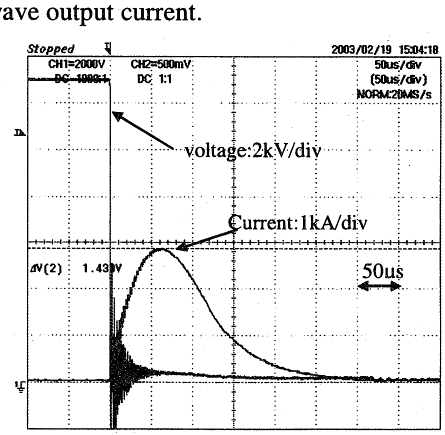

Figure7 Voltage and current wave of protection test.

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