INSTALLATION AND OPERATION OF NEW KLYSTRON POWER SUPPLY WITH FAST SOLID-STATE SWITCH FOR KLYSTRON PROTECTION AT THE PHOTON FACTORY STORAGE RING

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Abstract

In the 2.5-GeV Photon Factory (PF) storage ring at KEK, one of the klystron power supplies was upgraded during a summer shutdown in 2003. The new power supply can provide a DC high voltage of up to 45 kV with the maximum current of 9 A. To protect the klystron under sparks, a noble solid-state switch was incorporated. This paper describes the design and the performance of the new power supply.

INTRODUCTION

In the rf system [1] for the PF storage ring, four 500-MHz damped accelerating cavities are driven by four 200-kW klystrons (Toshiba, E3774). Each of the four power supplies for the klystrons can provide a typical voltage of 40 kV with a current of 8 A. The original power supplies were fabricated during 1979-1987; each consists of an Automatic Voltage Regulator (AVR) using magnetic amplifiers, a step-up transformer and a rectifier. Klystron protection is provided by a conventional crowbar circuit [2] using three ignitrons in series. Although these power supplies have been operated well, we anticipated future difficulty in maintaining them and proposed to update them gradually. As the first step of this renewal, we upgraded one of the power supplies in the summer of 2003.

High stability, low ripples, and good reliability are essential for the klystron power supply. To improve the performance mentioned above, we surveyed several modern designs in a similar manner to that presented in [3]. Initially, an existing power supply [4] for the NewSUBARU light source, which is based on an excellent high-frequency inverter technology, seemed to be very promising. However, we noticed that its modulation frequency (21.3 kHz) is close to our synchrotron frequency (23 kHz). We anticipated a potential problem that even small ripples at the modulation frequency can excite synchrotron oscillations. Thus, we adopted other design where both a conventional low-frequency converter and a noble solid-state switch for the klystron protection were used.

DESIGN

A block diagram of the new klystron power supply is shown in Fig. 1. A 3-phase input voltage of 6.6 kV is transformed to 440 V, and is regulated using thyristors. The voltage is then stepped up with a transformer, and is 12-phase rectified. The high voltage DC is smoothed using an LC filter, and is provided to the klystron through a fast solid-state switch. This switch is made up of 40 packages (two in a package) of Insulated Gate Bipolar Transistors (IGBT) which are connected in series. When the klystron experiences a spark, a short circuit current is initially limited by an inductance *L* of 10 mH. The above switch then turns the high voltage off quickly. We expect that this switch is more reliable than the conventional crowbar circuit, and is easier to maintain. In addition, the voltage drop in the input lines under sparks can be made small since this system does not shunt the currents. In a high-voltage cabinet, heater/anode power supplies are also incorporated. All control interfaces are so designed that they are compatible to those of the original one.

The above power supply was designed and fabricated in Nichicon Corporation. It was then installed in the Photon Factory. The principal components of the new power supply are shown in Fig. 2, except for the high-voltage

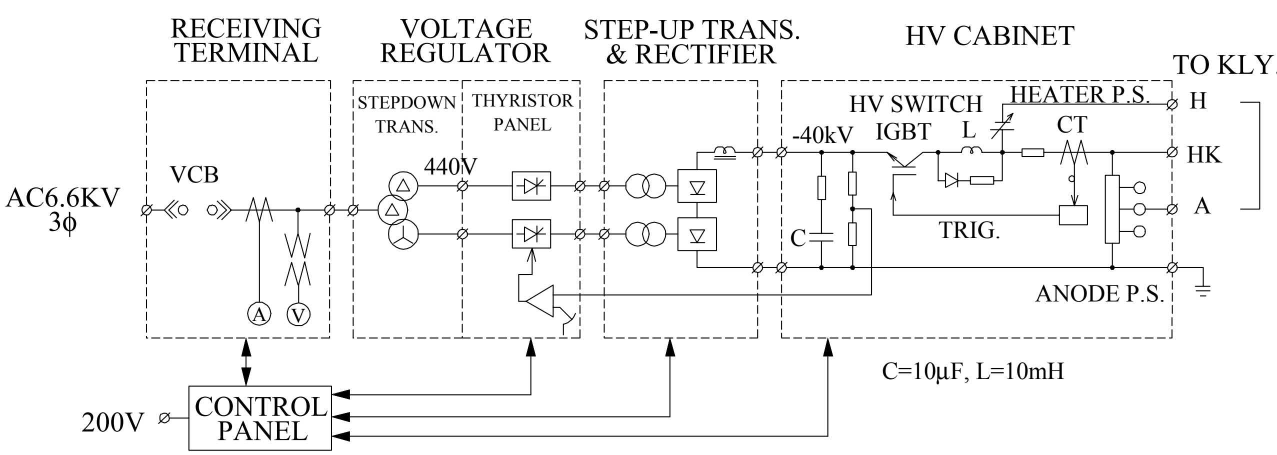

Figure 1: Block diagram of the new klystron power supply for the PF storage ring.

cabinet [1] which located separately.

Figure 2: New klystron power supply as installed.

PERFORMANCE TESTS

Ripples

Phase control angles for the thyristors were so adjusted that the high-voltage ripples were minimized at a typical operating voltage of 40 kV. The ripple, measured after the adjustment, is shown in Fig. 3. In the figure, both the ripples for the new and the original power supplies are indicated. A statistical analysis of the measured ripples is shown in Table 1. The ripple from the new power supply was reduced by a factor of two than that from the original one.

The result of the Fast Fourier Transform (FFT) of the measured ripples is shown in Fig. 4. The spectrum lines at the frequencies of 50, 100 and 300 Hz were principal for the new power supply, where the 50 Hz is the fundamental frequency of electricity.

We also measured a correlation between the ripple and the fluctuation in an output rf from the klystron. Both the phase- and amplitude-fluctuation were in proportional to the ripple voltage. The measured proportional constants were 20.1 degrees per kV for the phase fluctuation, and 3.3 % per kV for the amplitude fluctuation, respectively.

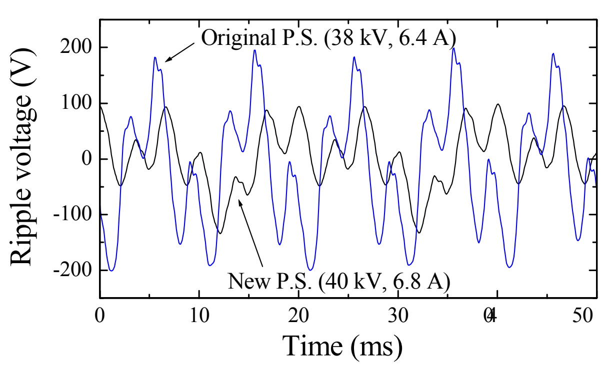

Figure 3: Measured ripples for the new and the original power supplies, respectively.

Table 1: Summary of the ripple voltages.

	New P.S.	Original P.S.
Peak to peak	233 V	423 V
r. m. s.	57 V	108 V

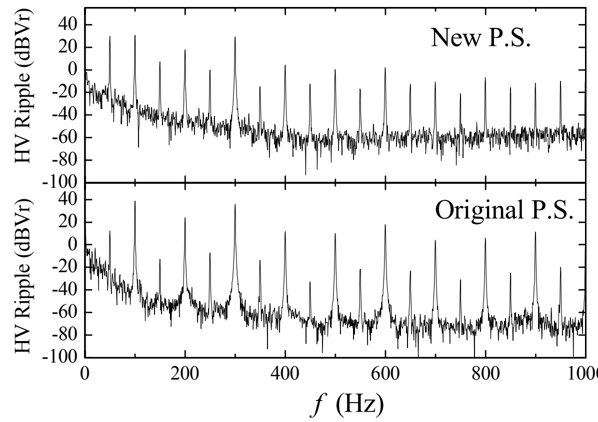

Figure 4: Spectra of the ripples for both power supplies. Hanning window was used upon the FFT. Ordinate: relative r.m.s. voltage to a reference voltage of 1 V (dB scale).

Under the storage ring operations, the above-mentioned rf fluctuations are stabilized by the feedback loops.

Stability

To stabilize the high output voltage, a picked-up signal from the output is fed back to the voltage regulator. After the feedback loop was adjusted, the stability of the high voltage was measured. The middle trace in Fig. 5 shows the variations in the high voltage during 24 hours. In the figure, other variations in both the input AC voltage and the output current are also shown for reference. A statistical analysis (see Table 2) of the above-mentioned data indicates that the high voltage fluctuated by 1% (peak-peak) when the input voltage varied by 4% (peak-peak).

In this power supply, the stability is determined by the gain and the frequency response of the feedback loop. In order to make this feedback less sensitive to any noise, we adjusted the response to be rather slow. As a result, high-frequency variations in the input voltage could not be compensated completely. The above stability is, however, fully acceptable for our requirement.

Table 2: Summary of the stability in the high voltage.

	Mean	Var. (p-p)	Var. (r.m.s.)
Input AC voltage	6.690 kV	4.0 %	0.55 %
DC high voltage	37.50 kV	1.0 %	0.07 %
Beam current	6.40 A	1.9 %	0.25 %

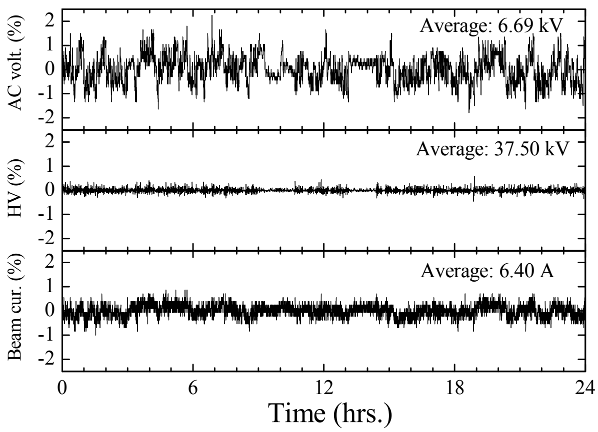

Figure 5: Stability in the high voltage of the new power supply. Relative variations in the input AC voltage, in the DC high voltage and in the klystron beam current are shown.

Short Circuit Test

To confirm the performance of the fast solid-state switch, we carried out a short circuit test under high voltages. For this purpose, a smoothing capacitor (indicated by *C* in Fig. 1) was charged while disconnecting the high-voltage cabinet from the upstream transformer. The output line (*HK*) was then connected to a short-circuit tester. Figure 6 shows a result of the test under a high voltage of 40 kV, where the short current was measured using a current transformer. After the output line was short-circuited to the ground, the short current increased gradually, having been limited by the inductance, and it was then turned off successfully. The solid-state switch started to work approximately 18 µs after the short. Note that the initial oscillation in the signal in Fig. 6 should be a noise due to the spark.

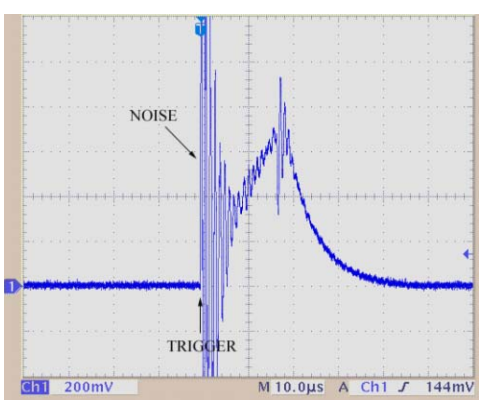

Figure 6: Result of the short circuit test. Ordinate: short circuit current (20 A/div.), abscissa: time (10 µs/div.).

Harmonic Currents

In many power supplies using thyristor regulation, higher harmonic currents arise in the input lines. To investigate whether they are within the capacity of our substation, we measured the harmonic currents in the new power supply. Figure 7 shows the measured harmonic currents under an output of 38 kV and 6.5 A. The fifth harmonic current (3.3 A) was the largest among the higher harmonics while the fundamental (50 Hz) current was 27.8 A. These harmonic currents can be shunt well by existing harmonic filters in our substation.

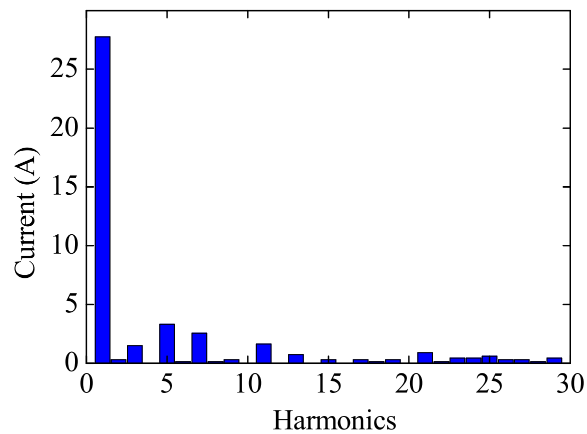

Figure 7: Measured harmonic currents (r.m.s.) in the input line. Per single phase.

CONCLUSION

One of the klystron power supplies for the Photon Factory storage ring was upgraded. A design, which is based on both a conventional conversion technology and a noble solid-state switch, was adopted. Low ripples, high stability and good reliability have been achieved. The solid-state switch for the klystron protection worked well under the test, where the high voltage could be cut off within 20 µs after the short. The new power supply has been working well since September, 2003, without any troubles.

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