PRESENT STATUS OF CAPACITOR-CHARGING POWER SUPPLIES FOR KLYSTRON MODULATORS IN SuperKEKB INJECTOR LINAC

M. Kawamura†, M. Akemoto, H. Nakajima, T. Natsui, T. Shidara, S. Fukuda, H. Honma, S Michizono, KEK, 305-0801 Tsukuba, Japan
O. Endo, H. Akikawa, K. Sato, Nihon Koshuha Co., Ltd., 226-0011 Yokohama, Japan

Abstract

Capacitor charging power supplies (CCPSs) have been used in compact klystron modulators. Two main types of CCPSs, the normal model and highly precise model, have been developed by Nihon Koshuha Co. in collaboration with KEK since JFY2012. In the KEK, regarding the output voltage stability of normal model, almost the same characteristic as the specification 0.2 %p-p was measured. After some repairs for the discharge problems, the CCPSs in the SuperKEKB injector linac were operated without important breakdown for about 6,000 h from autumn in 2017 to summer in 2018.

INTRODUCTION

The SuperKEKB injector linac has delivered electrons and positrons for particle physics and photon science experiments since 1982 [1]. At present, 59 S-band (2856 MHz) klystrons are used as RF sources in the injector.

One klystron modulator supplies pulsed high-power to one klystron. All klystron modulators have pulse-forming networks (PFNs). Thirteen compact klystron modulators [2-5] and 46 conventional klystron modulators [6] are now used. Regarding the charging method of PFN capacitors, compact modulator is a switching charging type using a capacitor-charging power supply (CCPS) [2-5,7-11], and conventional modulator is the resonant charging type. Further, the former is almost 1/3 the size of the latter.

Compact modulators and CCPSs have been developed since JFY2002 [3-5]. At first, the CCPSs were developed by Toshiba Electro-Wave Products Co. [3-5,7], and since JFY2012, they have been mainly developed by Nihon Koshuha Co. (NIKOHA) [8-11], in collaboration with KEK.

This article describes the present status of the CCPSs developed by NIKOHA. It includes the specifications, the difference between the normal model and the highly precise one, the measured results, and operation conditions in KEK.

OUTLINE OF NIKOHA CCPS

At present, 18 normal model CCPSs, two highly precise models and one exclusive model for the flux concentrator modulator [12] have been developed [11].

Figure 1 shows the outward appearances of the normal model and highly precise model, and Table 1 shows their specifications [8-11].

Figure 1: Outward appearances of the normal model (left) and highly precise model (right) of Nikoha CCPSs [11].

Figure 2 shows the schematic diagram of the 30 kJ/s normal model [8]. The normal model consists of three sections; the rectifier section,

Table 1: Specifications of the normal model and highly precise model of Nikoha CCPSs (for 0.62 μF load)

	Normal [8]	Highly Precise [9]
Input voltage	AC 420V±5% (3-phase)	
Charging power	30 kJ/s	35 kJ/s (Main: 30 kJ/s, Sub: 5kJ/s)
Output voltage	43 kV	
Average output current	1.6 A	1.8 A (Main:1.6 A, Sub:0.2 A)
Repetition rate	50 pps	50 pps
Output voltage stability	0.2 %p-p (at 43 kV)	0.03 %p-p (at 43 kV)
Efficiency	More than 80%	
Cooling	Water 5 L/min.	Water 5 L/min. (Main) Air (Sub)
Size (mm^3)	480×760×680	480×760×980

inverter section, and HV section.

The rectifier section converts 3-phase 420 V AC input to 600 V DC output. The inverter section is an IGBT-switched 20 kHz inverter, and it is constructed by two se-

† masato.kawamura@kek.jp

ries resonant circuits in parallel. The HV section is constructed by a high-frequency transformer and diode bridge circuits. The

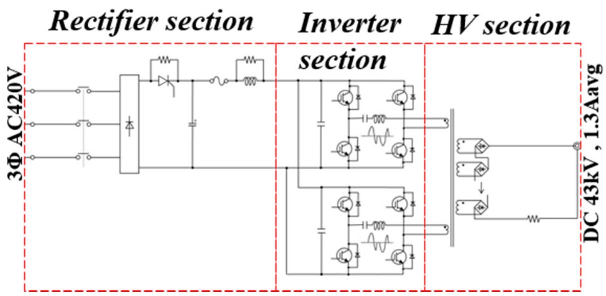

Figure 2: Schematic diagram of the normal model CCPS.

voltage ratio of transformer is more than one hundred times, and diode bridge circuit is constructed by ten full-wave rectifier devices in series. The HV section supplies at most 43 kV to the PFN capacitors.

This model controls two stages in the charging period. At the beginning of capacitor-charging, the two series resonant circuits operate in parallel to facilitate reduction in charging time (1st stage). When the capacitor voltage is close to the setting value, one series resonant circuit charges, to facilitate improvement of the peak voltage stability (2nd stage). The exclusive model for the flux concentrator modulator has a specification of 20 kV output voltage [10-11].

The highly precise model [9] is the CCPS where two power supplies (PSs) are combined as shown in Table 1; a 5 kJ/s PS (the sub PS) and a 30 kJ/s normal model (the main PS). The inverter section of the sub PS is constructed by one series resonant circuit, and the switching frequency is changed from 35 kHz to 17.5 kHz. The sub PS can be controlled by an optical signal for noise reduction.

In the highly precise model, the sub PS is connected to both loads (PFN capacitors) by a HV cable and upper dominance control equipment by control cables. The output HV cable from the main PS passes inside the sub PS. The sub PS generates control signals of the main PS. The highly precise model controls five stages in the charging period, using on-off operation of the three series resonant circuits and changing the switching frequency of the sub PS.

At the test in NIKOHA, the result of output voltage stabilities, namely 0.2%p-p of the normal model [8] and 0.022%p-p of the highly precise model [9], were observed.

All models of NIKOHA CCPSs are equipped with a function named "abnormal charge pulse set function". When a few incomplete charges being unrelated to important breakdown happen accidentally, the HV-off interlock doesn't function until the above situation counts successively to the established number of times. This function contributes the continuous operation.

PRESENT STATUS OF NIKOHA CCPS

At present, in the SuperKEKB injector linac, most compact klystron modulators use NIKOHA CCPSs at present. Since last summer, 12 NIKOHA CCPSs (and 1 Toshiba Electro-Wave Products Co. CCPS) have been operating [13].

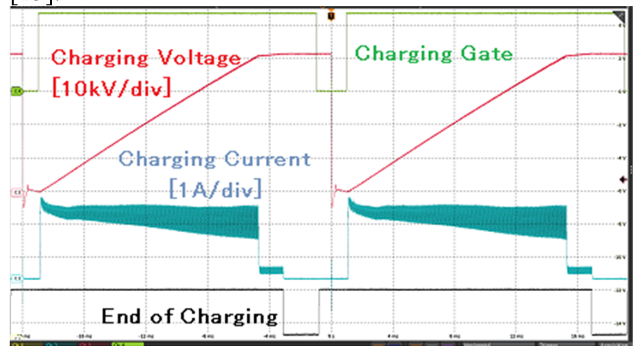

Figure 3: Waveforms of input-output signals of the normal model CCPS. The horizontal scale is 4 ms/div.

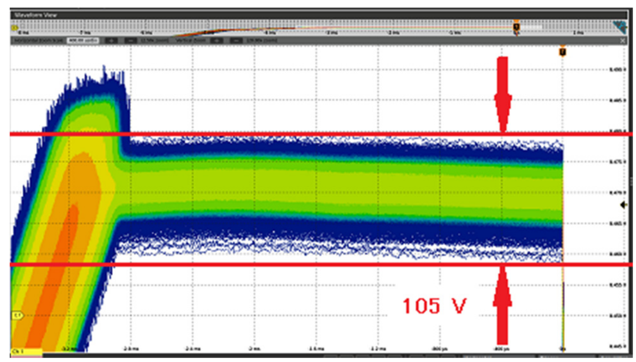

Figure 4: Collected flat-top zoomed-in signals of charging output voltage of normal model CCPS for 10 min. The horizontal scale is 200 μs/div.; the vertical scale is 25 V/div.

Characteristics of NIKOHA CCPS Measured in KEK

Figure 3 and 4 are the waveforms obtained at a KEK test station. The setting output voltage is 43 kV and the repetition rate is 50 pps. The waveforms of Fig. 3 are always indicated in all compact klystron modulators for confirming the state of CCPSs. The charging gate signal is input from the upper dominance control. The waveform of the charging gate signal shows that the ordered charging period is 18 ms. The charging voltage, current signals, and the end of charging signal are outputs from the CCPS. The waveforms of the charging voltage and current shows that the observed charging period is 16 ms and two stage control is accomplished.

The waveforms of Fig. 4 were measured to confirm the output voltage stability. There was a 105 V maximum unsteadiness at the flat-top for 10 min. Since the measured output voltage was 42.4 kV, the output voltage stability was calculated as 0.248%, which is very close to the specification. At the same time, using the histogram calculation function of the oscilloscope, a datum with the standard deviation σ of 26.6 V was obtained. Therefore, the error calculated as the absolute value of $\pm 2\sigma$ is 106 V, which is also very close to the above unsteadiness 105 V.

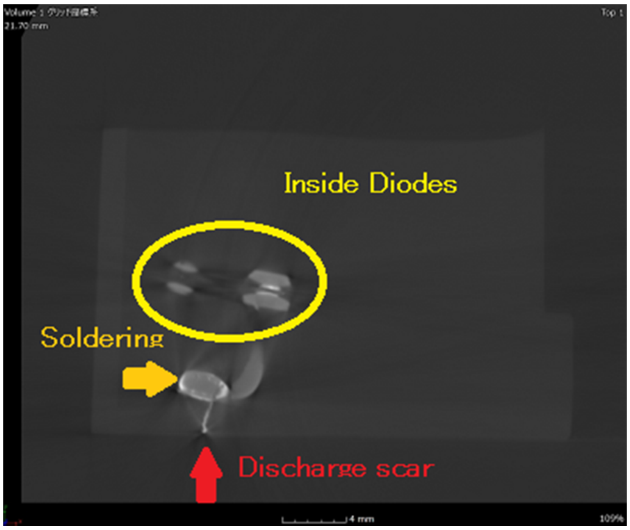

Figure 5: X-ray CT picture of a broken device [11].

Operation Conditions of CCPSs in SuperKEKB Injector Linac

The operating hours were greater than 5,000 h from autumn in 2015 to summer in 2016 [10], were about 3,600 h from autumn in 2016 to summer in 2017 [11] and were about 6,000 h from autumn in 2017 to summer in 2018 [13].

In October, 2015, two CCPSs broke down successively. The full-wave rectifier devices short-circuited. It seemed that the cause of the short was trash in the oil tank, which is built into the HV section of the CCPS. The check and cleaning of all CCPSs were performed in a clean room (a thermostat tank) [10].

In November, 2016, one CCPS broke down, but there was no trash in the oil tank. Non-destructive tests with X-ray computed tomography (X-ray CT) were commissioned to an outside agency (Tokyo Metropolitan Industrial Technology Research Institute, TIRI [14]) to confirm the situation inside the broken parts of the devices. Figure 5 is one of image data obtained by X-ray CT. Some discharge scars were observed from the soldering points. To avoid the discharge, both spacings for insulation of metal parts and shapes of the parts in the oil tank were reconsidered and changed in the broken CCPS [11].

After the repairs described above were performed, 12 CCPSs in the SuperKEKB injector linac were operated without breakdown from autumn in 2017 to summer in 2018 [13].

CONCLUSION

The NIKOHA CCPSs have been used by most compact klystron modulators, and after some repairs, their reliability is confirmed gradually by recent operation. In the future, longer operation will be performed, and the characteristics of the highly precise model will have to be measured in KEK.

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