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HIHG STABLE PULSE MODULATOR FOR PAL-XFEL*

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Abstract

The construction of Pohang Accelerator Laboratory X-ray Free Electron Laser (PAL-XFEL) was completed by the end of 2015. The commissioning began in April 2016, and the lasing of the hard X-ray FEL was achieved on end of 2016. The PAL-XFEL needs a highly stable electron beam. The very stable beam voltage of a klystron- modulator is essential to provide the stable acceleration field for an electron beam. Thus, the modulator system for the XFEL requires less than 50 ppm beam voltage stability. To get this high stability on the modulator system, the inverter type HVPS is a pivot component. And the modulator needs lower noise and more smart system. We report the stability of the pulse voltage and the test results of the pulse modulator.

INTRODUCTION

PAL-XFEL is a 4th generator light source, a coherent X-ray free electron laser (XFEL). The .RF stability is a key issue to get stable FEL output. The reasonably stable output requests the RF stability of 0.02% (rms) for both RF phase and amplitude. The modulator systems consist of 46 sets of 80 MW klystorns and 200 MW modulators to achieve 10 GeV energy for PAL XFEL. To get the RF phase stability of < 0.05 degree, the required beam voltage stability of the PAL XFEL will be < 50 ppm (rms). This requires that we need to use an ultra precision inverter power supply and a fine controller of feedback signal of the charging voltage in order to stabilize the PFN charging level. The proper conditioning of feedback signal with a thermally stable probe is necessary to realize an ultra stable charging performance [1]. And the modulator needs lower noise level and the heater power of the klystron and thyratron was trigger synchronised to the cluster part where the change was small.

PULSE MODULATOR SYSTEM

The pulse modulator system uses a constant current source such as an inverter power supply type.

High Power Klystron and Modulator

An inverter power supply is called capacitor charging power supply (CCPS) because it supplies constant current into the capacitors. In the CCPS, to turn off a thyraton switch in the modulator safely after every discharge, the next charging schedule, digitally safe system, is under short-circuit condition due to the current limit feature. With this CCPS, the modulator system will be naturally compact. These features are well matched to the next generation modulator for PAL XFEL facility. The CCPS power rating is 120 kJ/s. Total charging time is about 14 ms. The specifications of the modulator are output power of 200 MW, beam voltage of 400 kV, beam current of 500 A, pulse width of 8 μs and repetition rate of 60 Hz. To achieve those demands, we adopted the fine CCPS as well as the coarse CCPS. Table 1 summarizes the specification of the modulator. As a load s-band E37320 80 MW klystron will be matched to the modulator system. Fig. 1 shows the circuit diagram of a modulator using CCPS.

Table 1: PAL-XFEL Modulator Specifications

Discription	Unit	Value
Peak Power	MW max.	200
Repetition Rate	Hz (normal)	60
Pulse Voltage Stability	ppm	>50
Pulse Peak Voltage	kV	400
Pulse Peak Current	A	500
Pulse Width	μs	7.5
PFN Impedance	Ω	2.63
Main CCPS Power	kJ/s	120

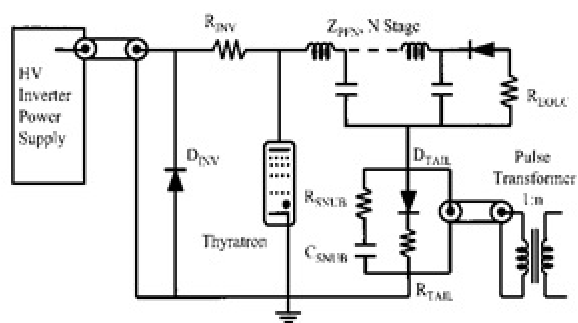

Figure 1: Circuit diagram of a modulator with a CCPS.

Inverter High Voltage Power Supply

To meet specifications of Table 1, two different types of current charging power supply (CCPS) are employed. One is a fine CCPS which is a high precision type (< 50 ppm) and the other is a coarse CCPS (< 1000 ppm). The coarse charging and fine charging is arranged to get the regulation with optimum power sharing. Figure 2 shows the charging schedule with parallel operation of inverters [2]. Total charging time T_c and charging voltage V_o are given by

$$(m+n)\, t_o = T_c\,,\; m\,(D + d) + n\,d = V_o\,,$$
$$n\,d = V_o - V = j\,D\,,$$
$$m+n = a,\; m^2 - a\,m + (a + b)\,j = 0\,,$$

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where inverter switching time $t_o = 1/f_r$, T_c is total charging time, m is total switching number of coarse charging, n is total switching number of fine charging, $a = T_c / t_o$, fine charging step $d = I_f\, t_o / C$, coarse charging step $D = (I_c + I_f)\, t_o / C$, C is a load capacitance, I_f is charging current of a fine inverter, I_c is charging current of a coarse inverter.

Typical parameters for PAL XFEL modulator are PRR = 60 Hz, f_r = 50 kHz, V_o =50 kV, C =1.4 μF, b = 10,000. Then T_c = 16.7 ms, t_o = 20.0 μs, a = 835, P_{av} = 120 kJ/s.

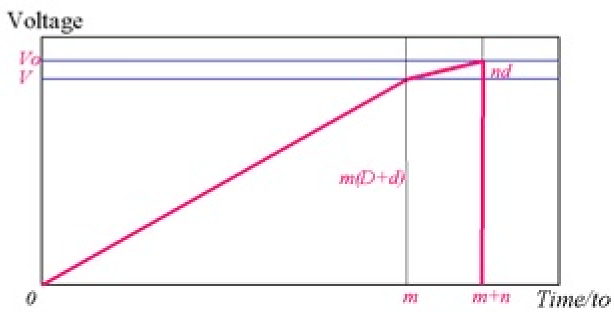

Figure 2: Charging Scheme in Parallel Operation.

Paraday Cage Type Modulator and Klystron

We used a faraday cage circuit to reduce EMI noise. The modulator and klystron are configured in one faraday cage form in order to remove the noise generated by the switching of the thyratron. Fig. 3 shows a faraday cage consisting of modulator and klystron.

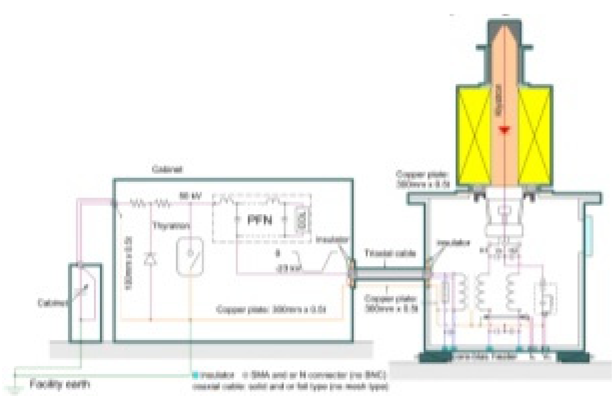

Figure 3: Faraday cage consisting of modulator and klystron.

Stability Measurement

The 50 ppm beam voltage stability measurement setup is shown in Fig. 4. The beam voltage signal was obtained at 10,000:1 CVD installed in insulating oil cooling with cooling water. On the beam voltage waveform, the zero offset is defined by a differential amplifier (DA1855A, Lecroy) setting a band width of 1 MHz [2,3]. To display the histogram, an oscilloscope (DPO7104, Tektronix) equipped with a high resolution mode (11bit) in an acquisition mode is used. The beam voltage stability measurement test is performed at 42kV, maximum voltage of modulator and 1 hour later, sufficient time for temperature of modulator panel inside to saturate. Test environments are as following;

1) oscilloscope, differential amplifier, trigger generator : warming up 1hour,
2) CCPS, master controller: warming up 1 hour (60Hz @ 35kV),
3) maximum PFN voltage is 42 kV and repetition rate 60 Hz at ambient temperature: 20~25℃ and humidity: 10~25%,
4) trigger signal synchronized with AC line frequency at thyratron AC heater power.

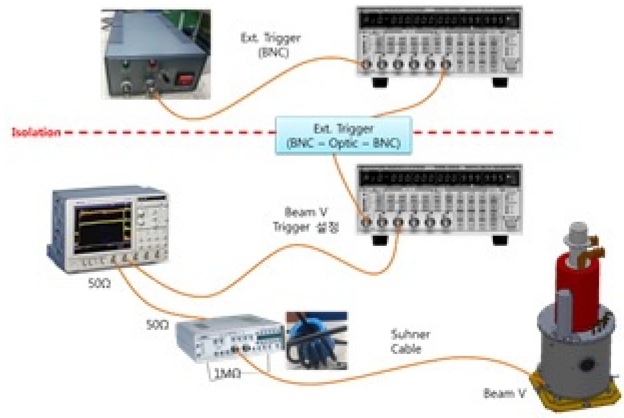

Figure 4: Beam voltage stability measurement setup.

RESULTS OF TEST

The experimental setup is shown in Figure 5 for the 200 MW modulator system with 80 MW klystron load. The used DC source power supply consists of 3 coarse CCPSs (each 30 kJ/s) and 1 coarse and fine CCPS (35 kJ/s) controlled by a digital signal processing (DSP). The operation condition of the modulator is repetition rate 60 Hz, PFN charging voltage 42 kV, pulse width 7.5 μs.

Figure 5: Experiment setup for the modulator system.

Figure 6 shows the waveform of the PFN voltage when it is charging. The blue line indicates PFN charging voltage and the green line shows resonant current. The total capacitor is 1.4 μF.

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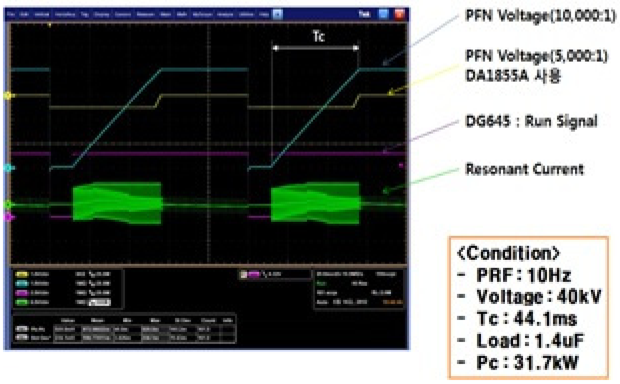

Figure 6: PFN charging voltage waveform and resonant current.

Figure 7 shows detailed charging waveform of each bucket. The size of average charging voltage step is 34 V from the coarse CCPS. The resonant switching frequency is 40 kHz. The waveform in the lower part of the right figure shows charging voltage step by means of coarse CCPS, fine CCPS in pulse width modulation and fine CCPS in high regulation mode subsequently. In the regulation mode, the charging voltage step is about 2 V.

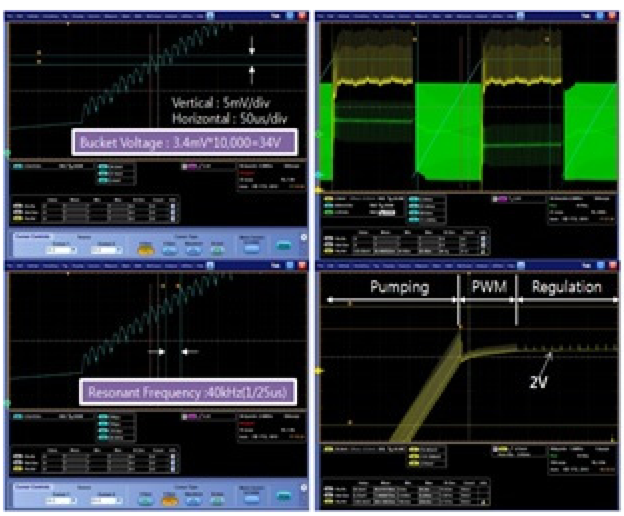

Figure 7: Detail waveform of PFN charging voltage (one bucket voltage of 34 V, resonant frequency of 40 kHz, regulation voltage of 2 V)

Figure 8 shows the stability measurement waveform of the beam voltage. The measurement value of beam voltage is 21.53 ppm at 42 kV PFN voltage, 60 Hz repetition rate.

Figure 9 shows the variation of beam voltage stability measured 8 times, which is measured as about 3.8 ppm. The stability test conditions of the modulator were 60 Hz, 42 kV PFN charging voltage.

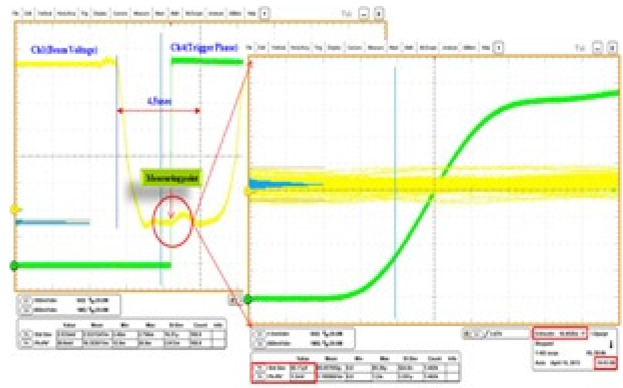

Figure 8: Stability measurement of the beam voltage (1 mV/div, 5 ns/div) 21.53 ppm (85.17 V/39.554 V=21.53 ppm).

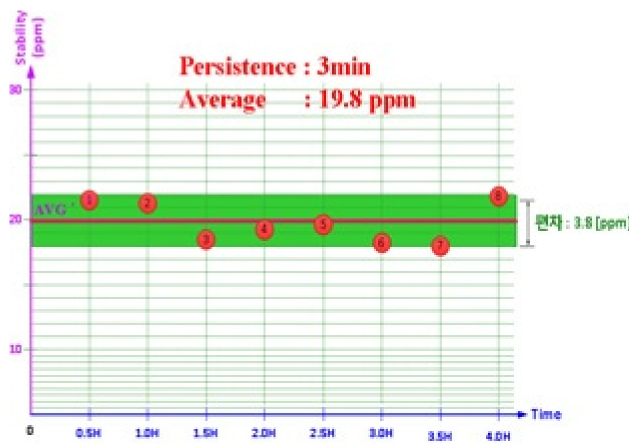

Figure 9: Beam voltage Stability of the modulator (Standard deviation 3.8 ppm).

SUMMARY

PAL developed DC source power supply consists of 3 coarse CCPSs (each 30 kJ/s) and 1 coarse and fine CCPS (35 kJ/s) controlled by a digital signal processing (DSP). The CCPS system was applied to the 200 MW modulator in order to obtain highly stable beam voltage with a repetition rate of 60 Hz. The result of the beam voltage stability was < 50 ppm satisfying the requirement.

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