PAL XFEL PULSE MODULATOR SYSTEM TEST RESULTS USING A HIGH PRECISION CCPS*

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Abstract

PAL XFEL is supposed to install 51 units of the pulse modulator power supplies for a 10-GeV linear accelerator using S-band (2856 MHz) cavities. The requirements of the modulator stability really become very tight. The stability on beam voltage is required to be less than 50 ppm. In order to obtain the high precision stability from the modulator system, we have newly produced a capacitor charging power supply (CCPS) and obtained the target stability with 10 ppm (STD) accuracy from measuring PFN (Pulse Forming Network). The CCPS generates a maximum output voltage of 50 kV at average current of 2.4 A with 4 units of the CCPS. The modulator peak output capacity is 400 kV, 500 A and 7.5 μs at a pulse repetition rate of 60 pps using CCPS, a modified type-E PFN, and a pulse transformer. In this paper, the test results of the modulator system will be described.

INTRODUCTION

In order to obtain the energy of 10 GeV from PAL XFEL, We are expecting to employ 51 units of pulse modulators with matching klystrons. Among the 51 units, s-band types are fifty units, and x-band type is one. The requirements of a beam voltage stability and RF phase stability are 0.005% (std) and 0.1 degree (std), respectively. The high precision CCPS has been employed to meet the requirement for the modulator stability. We are supposed to use three types of klystrons: an equal number of modulators with 48 of the s-band 80 MW klystrons, two of the s-band 25 MW klystrons, and one of the x-band klystron.

MODULATOR SYSTEM

51 units of the pulse modulator power supplies will be installed for a 10-GeV linear accelerator until the end of September this year. There are three types of klystrons: the s-band 80 MW, 25 MW klystrons, and the x-band 50 MW klystron.

Klystron Tube

The performance parameters of the s-band Toshiba E37320 klystrons and XL4 klystron are shown in the tables below. The XL4, x-band klystron, is used to power x-band structures of PAL XFEL for beam phase space linearization.

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Table 1: S-band Klystron Specifications

Description	Unit	Value
Frequency	MHz	2,856
Peak output RF power	MW	80
RF pulse	μs	4
Cathode voltage (V_k)	kV	400
Beam current (I_k)	A	500
μ-perveance		1.85~2.0
Repetition rate (Max)	Hz	60

Table 2: X-band Klystron Specifications

Description	Unit	Value
Frequency	GHz	11,424
Peak output RF power	MW	50
RF pulse	μs	2
Cathode voltage (V_k)	kV	450
Beam current (I_k)	A	360
μ-perveance		1.2
Repetition rate (Max)	Hz	120

Modulator

The specifications of the PAL XFEL modulator are output power of 200 MW, beam voltage of 400 kV, beam current of 500 A, pulse width of 7.5 μs and repetition rate of 60 Hz. Table 3 summarizes the specifications of the modulator.

Table 3: Modulator Specifications

Description	Unit	Value
Peak power	MW	200
Average charging power	kW	120
Repetition rate (normal)	Hz	60
Pulse peak output voltage	kV	400
Pulse peak output current	A	500
PFN voltage stability (rms)	ppm	< 10
Flat-top width	μs	4.0

Figure 1 shows the simplified circuit diagram of the PAL XFEL modulator. In order to charge to PFN capacitor, CCPS are used, which are newly produced by

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Dawonsys and Posco ICT. The inverter power supply is a constant current source so that the PFN voltage is linearly increasing during active charging time. It takes about 14 msec to charge the PFN up to 45 kV, not including dwell time as using a maximum output voltage of 50 kV at an average current of 2.4 A with 4 units of the CCPS in a 200 MW PAL XFEL modulator. The CCPS total power rating is 120 kJ/s.

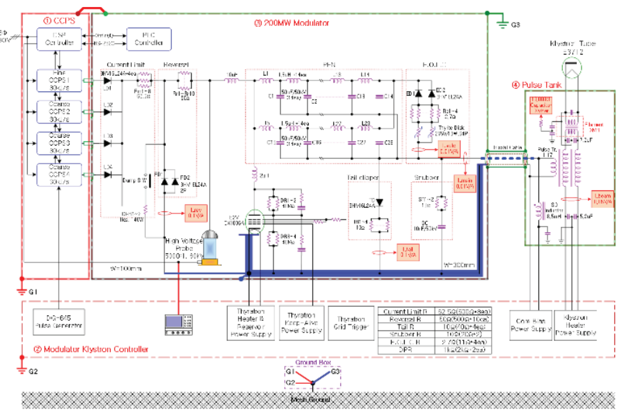

Figure 1: Circuit diagram of the PALXFEL modulator.

CAPACITOR CHARGING POWER SUPPLY

The modulator employees a high efficiency capacitor charging power supply that utilizes a high frequency, series resonant inverter topology. The power supply is specifically designed for constant current capacitor charging. With the help of the CCPS, the modulator system is naturally compact in spite of a 200 MW modulator power.

Configuration of CCPS

The block diagram of the inverter power supply is shown in Fig. 2. There are four basic modules: the input power module, the inverter section, the high-voltage tank, and the control system. Inverter part is a resonance method that consists of L and C to supply resonance current and full-bridge circuit using IGBT module. The resonance frequency is 40 kHz. High voltage rectifier circuits produce the rectified high voltage output. The control circuit utilizes a high regulation scheme that DSP 28335 is used to control primary power and inverter part of the CCPS, sensing output voltage and current in order to monitor various interlocks.

Control of CCPS

CCPS controls PFN voltage precisely by using a precision controller and a master controller. Figure 3 shows the configuration for precision control. The precision controller picks up the charged voltage in PFN by using a high voltage probe and transfers to a master controller in the CCPS after determining the gate pulse width of the IGBT to maintain setting value of the PFN charging voltage through a P-I control. The master controller controls the output by transmitting the gate

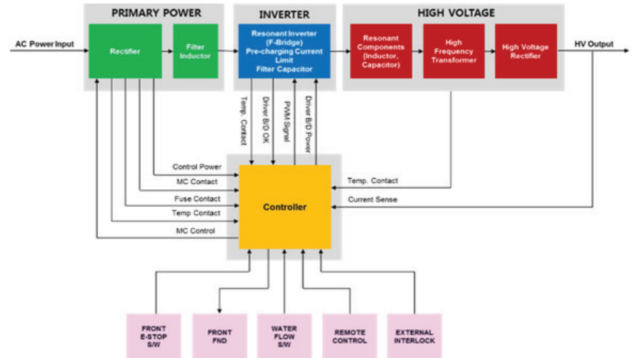

Figure 2: Block diagram of the inverter power supply.

signal of IGBT received from a precision controller and displays received interlock information of CCPS, then finally transfers the information to a machine controller. To meet a very tight stability two different types of CCPS mode are employed. One is a fine control mode which is a high precision type (< 10 ppm) and the other is a coarse CCPS (<1,000 ppm).

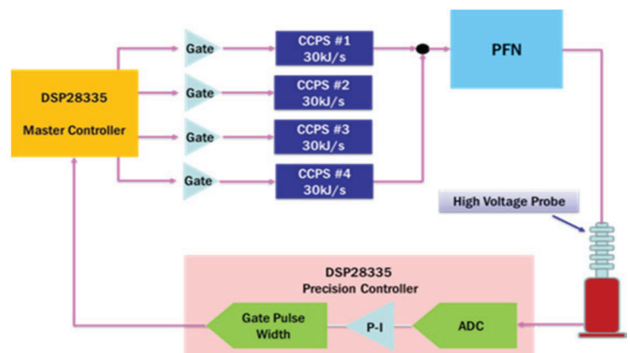

Figure 3: CCPS precision control configuration.

Stability Measurement

The experimental devices were set up to measure the modulator stability from PFN, beam voltage, and beam current as shown in Fig. 4. To obtain high precision of the voltage stability, we used a high voltage probe (VD60 Ross) which is very stable in temperature fluctuation. On the PFN, beam voltage, and beam current waveform, the zero offset is defined by a differential amplifier (DA1855A, Lecroy) setting a band width of 100 kHz. To

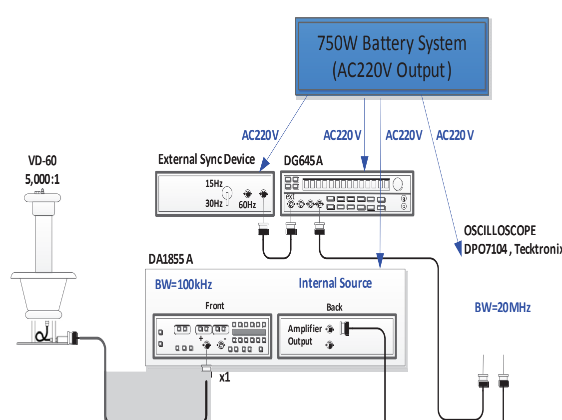

Figure 4: Test device for a stability measurement.

display the histogram, an oscilloscope (DPO7104, Tektronix) equipped with a high resolution mode in an acquisition mode is used [1].

PFN Charging Voltage Waveform

The capacitance of PFN in the 200 MW PAL XFEL modulator is 1.4 μs, and the test operation condition is 42 kV at 60 Hz. The load is Toshiba s-band klystron (E37320). Figure 5 shows the charging current waveform of PFN and bucket voltage during charging. The charging voltage will be changed when the PFN voltage reaches to the target value during charging. Figure 6 shows the expanded precision charging voltage waveform and control of voltage waveform in the regulation section of PFN. The size of the precision voltage in the regulation section is less than 2 V.

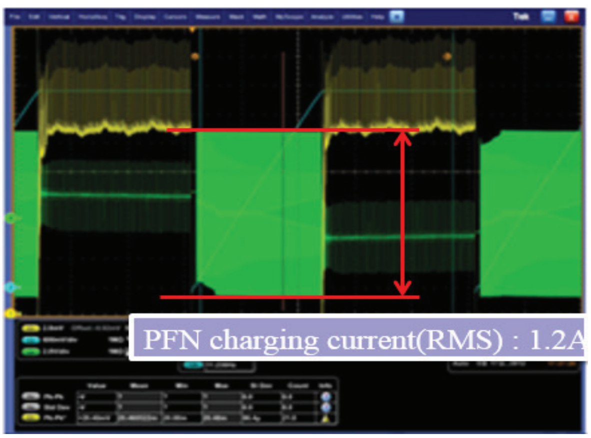

Figure 5: PFN charging current.

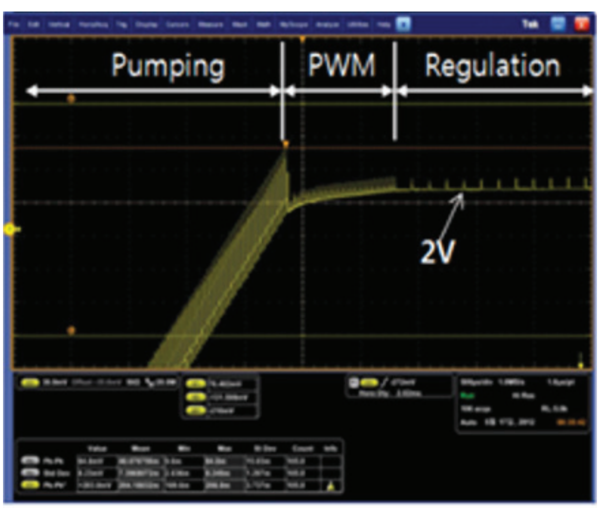

Figure 6: Current of PFN charging voltage.

Test Results

In order to reduce switching noise from a thyratron switch in a modulator system, separated AC power and optic cables were used to block the switching noise while measuring the stability of PFN voltage. The measuring position of PFN stability is 1 μs before switching of a thyratron. For each measurement it took about 3 minutes and performed 3 times after every 30 minutes waiting time. The stability of the PFN charging voltage was about 9 ppm shown in Fig. 7. In the same method as PFN measuring, the beam voltage stability was trying to do, and the measuring position of beam voltage stability was randomly selected from the flat-top, then set 5 ns for the time division. For each measurement it took about 3 minutes and performed 8 times for more accurate results after every 30 minutes waiting time. The stability of the beam voltage was about 29.6 ppm shown in Fig. 8. The slight deviation of the stability for each step was mainly due to temperature dependent time variation.

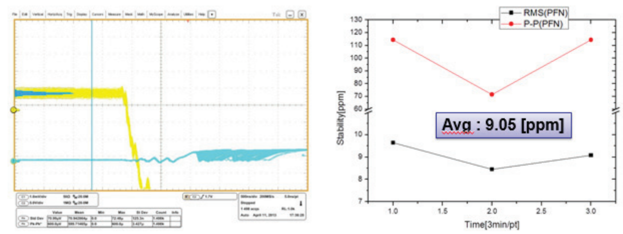

Figure 7: PFN voltage stability measurement.

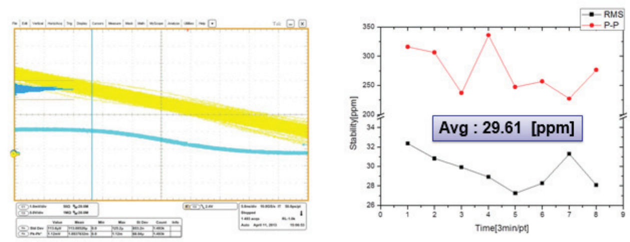

Figure 8: Beam voltage stability measurement.

HARMONICS OF CCPS INPUT POWER MEASUREMENT

We measured and analysed the harmonics that may be generated from CCPS input power, 480 V AC while the CCPS is running at 40 kV, 60 Hz. Plots for current waveforms measured from the 480 V AC are shown in Fig. 9.

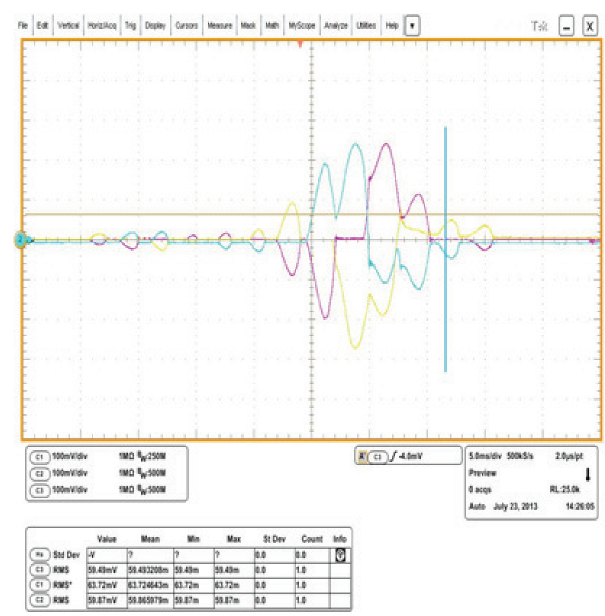

Figure 9: Current waveforms from AC 480 V.

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The detailed harmonic trends measured from AC 480 V are summarized below while CCPS is working at 40 kV, 60 Hz. As shown in Fig. 10, those are 41.6 % of the 2nd harmonics, 14.7 % of 3rd, 30.7 % of 5th, and 10 % of 7th. As a result of analysing each phase and its harmonics, unexpected high harmonic distortions have occurred due to characteristic of making the CCPS operation that they are only working during the period of 13.4 ms at 60 Hz. An inductor of 1 mH was set up in the input source side of AC 480 V to solve that harmonic problem. After that there was a reduction effect of about 72 % at harmonic distortions. However, the voltage drops of AC 480 V get worse at the inductor test of 1 mH, so we need to consider an inductor of the appropriate values. In general, the inductor of installed capacity of 5 % is applied for harmonic current reduction of nonlinear load. Therefore, the inductor of about 5 % is expected to apply an inductor of around 600 μH when used shall be. The harmonics also bring the reduction by increasing capacitor values that used in the DC link in the CCPS.

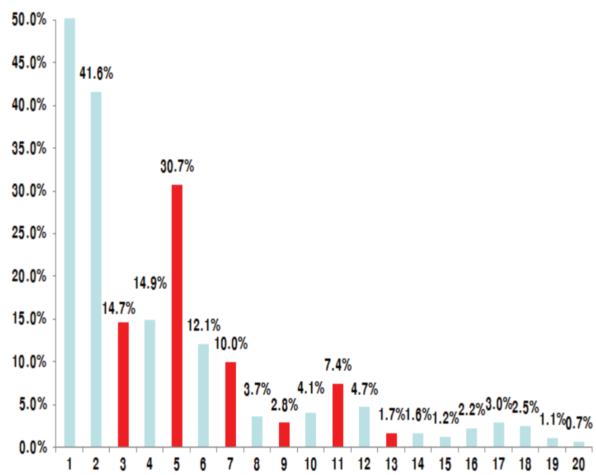

Figure 10: Harmonic current spectrum measured from AC 480 V.

CONCLUSION

The 200 MW pulse modulator for an 80 MW s-band klystron was designed and fabricated including a precise function of CCPS that is a maximum output voltage of 50 kV and an average power of 30 kW. The stability results of measuring at PFN and beam voltage were satisfying the requirement of < 10 ppm and < 50 ppm, respectively. Three-phase 480 V AC is used to supply CCPS input with the AC power. We have found lots of power factor measured more badly than the requirements set out while CCPS is working only for 13.3 ms at 60 Hz. In order to reduce unexpected high harmonic distortions we have to make a harmonic measurement of AC 480 V applied to CCPS input lines, then installed a inductor of 600 mH between CCPS input lines and AC 480 V. After that, we are satisfying the results due to reducing the high harmonic distortions and the voltage drop rate of AC 480 V.

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[1] J.S. Oh, S.S. Park, Y.J. Han, I.S. Ko, W. Namkung, "Design considerations for the stability improvement of klystron-modulator for PAL-XFEL", Proceeding of 2005 Particle Accelerator Conference, Knoxville, Tennessee, 2005, pp. 1165-1167.

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