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Design and Upgrading of HLS Linac Modulators

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Abstract The upgrading project of the HLS (Hefei Light Source) klystron modulators was firstly introduced. Constant-current, switch-mode, PFN charging power supplies were adopted in the new design. Charging parameters were calculated. Simulation model of main discharging circuit was established. An emphasis of analysis was put on the reversal voltage problem. A protection circuit was designed based on the simulation results and reversal voltage study. Major waveforms measured from daily operation were presented. Finally new control system of the modulators was described.

Key words modulator, PFN, constant-current switch-mode power supply, simulation, protection circuit, control

1 Introduction

Before the Phase Ⅱ Project of National Synchrotron Radiation Laboratory (NSRL), the klystron modulators of the HLS 200 MeV Linac employed 50Hz high voltage power supplies and resonant charging scheme with De-Qing circuit[1,2]. The 50Hz high voltage charging power consists of four basic components which include a 50kVA motorized 3-phase variable transformer, a high voltage step-up transformer, a rectifier assembly and a charging inductance as shown in Fig.1. After more than ten years' operation, some components were no longer in good condition and circuit failure occurred often. The stability of the output high voltage was not satisfactory, especially when the AC line voltage fluctuated. The control and monitor of the modulators was based on relay circuit and manual operation. There was no computerized controller in the modulators and therefore can not meet the requirement of the new EPICS control system of the HLS[3].

In order to increase the stability, operation reliability and follow the standard of the HLS EPICS system, an upgrading project was initiated in 2002. The project includes two major parts. One is the replacement of the old HV powers with five LC1202/40kV constant-current charging powers. The other is the addition of a PLC in each modulator as the local machine controller. The old control and monitor system were totally abandoned. Because LC1202 works at a frequency of 40 kHz and uses water cooling method, it is very compact in size. Much space in modulator cabinet is free out. The volume and weight of a new charging power reduces about 20 times compared with the old one.

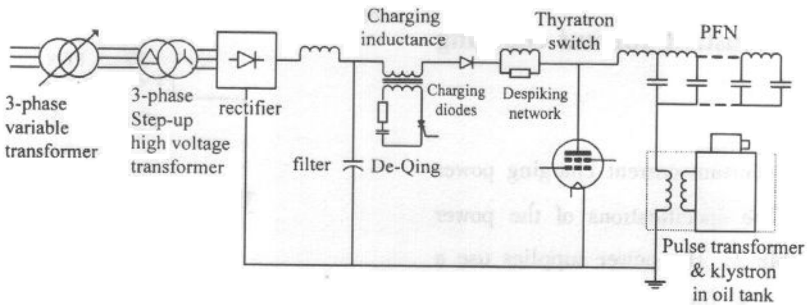

Fig.1. Schematic diagram of the old modulators.

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Fig.2 shows the structure of the new modulator after modification. The major parameters of the modulators are listed in table 1.

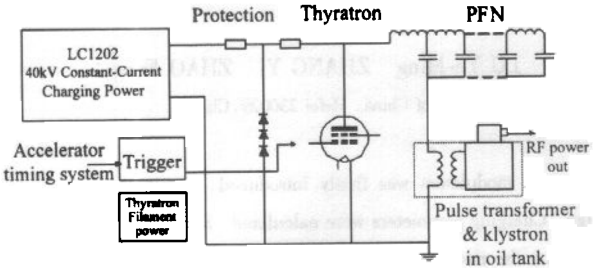

Fig.2. New klystron modulator structure.

Table 1. Specifications of HLS klystron modulators

Klystron	KMF-1017A
Modulator Peak power	50MW
Maximum average power	12kW
Klystron Beam voltage	250kV
Klystron Beam Current	240A
Peak RF output power	15MW
Thyratron anode voltage	40kV
Thyratron current	2.9kA
Pulse flat top width	2μs
Repetition rate	50pps
PFN impedance	8.7Ω
Pulse to pulse repeatability	<0.5%

2 New high voltage constant-current charging power supply[4,5]

Five LC1202/40kV constant-current charging power supplies are employed. The specifications of the power supplies are listed in Table 2. The power supplies use a parallel resonant topology and the working switching frequency is higher than the resonant frequency to achieve the constant current charging.

Table 2. Specifications of LC1202/40kV power supply.

Average charging rate	12kJ/s
Peak charging rate	13.5kJ/s
Linearity	±1% of full scale
Accuracy	±1% of rated output
power factor	>0.9
Efficiency	>90%
Stability	<0.2%/h after 1 hour warmup
Pulse repeatability	±0.1%

When the LC1202 is connected to PFN, the charging time in each charging cycle can be calculated as

$$T_C = \frac{1}{2}(CV^2)/P_C, \quad (1)$$

where $C = 22nF$ is the total capacitance of PFN, $V = 40kV$ is the charging voltage and $P_C = 13.5kJ/s$ is the peak charging rate. Then T_C can be obtained as 12.4ms. After the charging voltage is reached, there is a waiting time before discharging. The repetition rate of the modulator is 50Hz and therefore the waiting time is 20 - 12.4 = 7.6ms. The average charging rate can be got as

$$\bar{P} = \frac{1}{2}(CV^2)/T, \quad (2)$$

which reaches 8.8kJ/s. The maximum repetition rate that can be achieved by the new power supply is 1/12.4ms = 80.6Hz.

3 Simulation of the main discharging circuit

A pspice model of the main discharging circuit is established as shown in Fig.3. The model includes a PFN, a pulse transformer, a thyratron switch and a load. The modelling of pulse transformer is based on LC meter's measurement. The parameters include leakage inductance, coupling coefficient, etc. The thyratron model is obtained by modifying forward and reversal characteristic of a diode model. The modelling of these two elements is

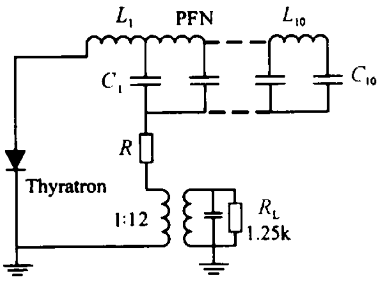

Fig.3. Pspice model of main discharging circuit.

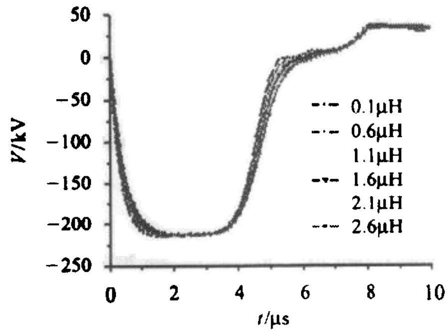

Fig.4. Pulse waveform changes with L1.

very important because the accuracy of simulation depends largely on their parameters.

Fig4. shows that the pulse rise slope changes with $L1$ sensitively. Fig.5 and Fig.6 shows when the load impedance changes, for example, in a fault mode during discharging, the pulse waveforms and reversal voltage across the PFN change accordingly. These results can be a reference when designing the protection circuit.

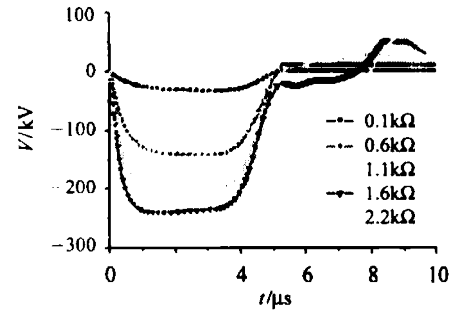

Fig.5. Pulse waveform changes with R-load.

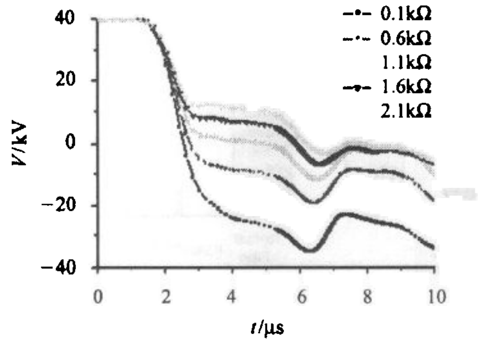

Fig.6. Reversal voltages change with R-load.

4 New Protection circuit design

When the HV powers are connected to the PFN with a coaxial cable, the cable capacitance C_c may discharge through thyratron and the reverse energy propagates back to the HV power output stage. A transient current flows through the rectifier diode Ds which can cause the damage of Ds. A resistor R_t, which is equal or greater than the characteristic impedance of the cable, can be used to limit the current, as referred in Fig.8.

Another reversal voltage comes from the mismatch of the PFN and the load. Normally the circuit is underdamped, and there is an inherent reversal voltage. The reversal is very large when a corona happens in the HV load. The current can damage the Ds imside the HV power as illustrated in Fig 7.

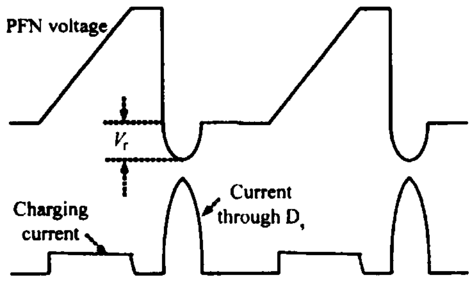

Fig.7. Current through D_s caused by PFN reversal voltage

If I_r is greater than the supply rated output current, which is $I_r = V_r/R_t \geqslant I_{charging}$, then a protection D should be used. The key parameters which should be considered when selecting the diode D are reversal voltage rating, RMS current rating and forward voltage drop. The reversal voltage rating must be greater than the operating voltage, and the RMS current rating must be greater than the current due to load voltage reversals. It can be determined as:

$$I_{rms} > \frac{V_r}{\sqrt{2}R_t}\sqrt{d}, \tag{3}$$

where V_r is the reversal voltage, d is the duty cycle of the reversal event. If the forward voltage drop of D is not small enough, then another resistor R'_t can be used as shown in Fig.8. Then the reversal voltage is clamped to V_f(D's forward drop).

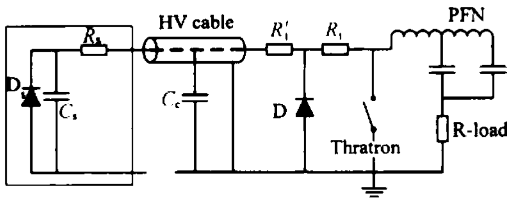

Fig.8. Protection circuit model

For the selection of R_t and R_t', physical size should be sufficient to ensure the voltage holdoff capacity.

The power dissipation in R can be calculated as:

$$P = I_{rms\text{-}charging} \times (R_t + R_t') + \frac{1}{2}(C_c + C_s)V^2 f, \tag{4}$$

which is about 160W. Finally, model 2DL50kV/1A diode is selected as D and three 50Ω/250W resistors in series are used as both R_t and R_t'.

5 Performance

The modulators have performed well since operation from Sep. 2002. Fig. 9 shows the PFN is charged to about 33kV. After discharging, the HV power is given an inhibit signal of 4ms width to avoid thyratron continual conducting. Fig. 10(a) is the load voltage waveform sampled from a high voltage capacitor divider, which is installed in the oil tank. The attenuation ratio of voltage divider is about 4200:1. Fig. 10(b) indicates the reversal voltage is no more than 10 % of positive voltage. A stability measurement shows that the pulse to pulse repeatability of the modulators is less than ±0.1 %.

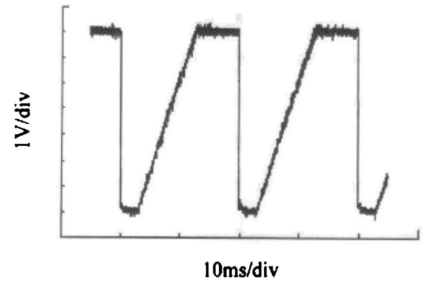

Fig. 9. PFN high voltage charging waveform.

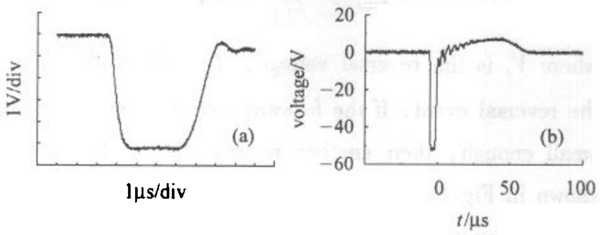

Fig. 10. Pulse generated by PFN discharging.

6 Modulator control

The new control system of the NSRL is built upon EPICS, following the standard model. The klystron modulator system control will be a subsystem as shown in Fig. 11. In each modulator, an OMRON PLC C200HE is employed as the local device controller. Command control, status-monitor, safety interlock and real-time communication with the IOC are achieved by the PLC. The protocol between the IOC and PLC is HOSLINK which is a vendor protocol. The relevant drivers in the IOC are developed. Several modules are adopted in each PLC including a 16-point Digital Input (DI) module, a 16-point Digital Output (DO), an 8-channel AD/DA module and a communication module. All the digital in/out signals are optically insulated. The strong electromagnetic interference, which is caused by the large pulse current in the modulator, is restrained. The program is written in the form of Relay Logic Ladder. The PLC makes the operation of the modulator more stable and reliable.

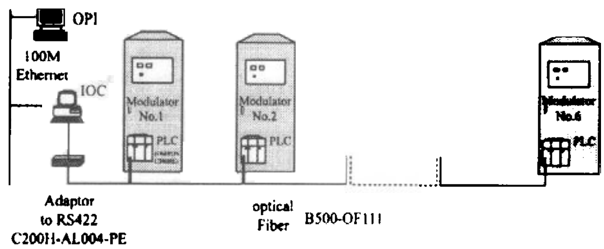

Fig. 11. Klystron modulators control structure.

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HLS 直线加速器调制器系统设计与改造*

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摘要　介绍了合肥同步辐射光源速调管调制器改造项目. 在新的设计中采用了开关型恒流 PFN 充电电源,计算了充电参数,建立了主放电回路的仿真模型,重点分析了电路中反向电压问题,依据仿真结果及分析设计了反向保护电路. 给出了运行中的主要波形. 最后介绍了新的调制器控制系统.

关键词　调制器　PFN　恒流逆变高压电源　模拟　保护电路　控制

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