

산업용 가속기용 고출력 펄스시스템의 설계와 시험

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Design and Test Results of High-Power Pulse Generator System for Industrial Accelerator Application

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Abstract - A conventional linear accelerator system requires a flat-topped pulse with less than ± 0.5% ripple to meet the beam energy spread requirements and to improve pulse efficiency of RF systems. A line-type pulsed modulator is widely used in pulsed power circuits for applications such as accelerators, radar, medical radiation, or ionization systems. The high-voltage pulse generator system with an output voltage of 284 kV, a pulse width of 10 μs, and a rise time of 0.84 μs has been designed and fabricated to drive a klystron which has 30-MW peak and 60-kW average RF output power. The high-voltage test was performed using the klystron load.

This thesis describes the design and test results of high-power pulse generator system for industrial accelerator application. The experimental results were analyzed and compared with the design.

I. INTRODUCTION

An industrial linear accelerator system for E-beam sterilization is under development for bio-technology applications. It can be used to improve the properties of macromolecular materials or to sterilize medical equipment and farm products. This accelerator system requires a flat-topped pulse with less than ± 0.5% ripple to meet the beam energy spread requirements and to improve pulse efficiency of RF systems.

In the linear accelerators, a pulse modulator system with a line-type PFN can be used to drive a high-power klystron as a pulsed RF source amplifier. The pulse modulator with a pulse width of 10 μs, a rise time of 0.84 μs, and a pulse droop of 2.9% has been designed and tested to drive a klystron which has an output voltage of 284 kV, 30-MW peak and 60-kW average RF output power. In this paper, the pulse generator system was investigated and analyzed with the pulse response characteristics using a simplified equivalent circuit model. The pulse rise characteristics are simplified and generalized for a high-power klystron. The practical limitations on the rise time are discussed. The experimental results are analyzed and compared with the design.

II. DESIGN BACKGROUNDS

A. Equivalent circuit analysis

A pulse transformer and its associated pulse generator and load can be represented by an equivalent circuit.

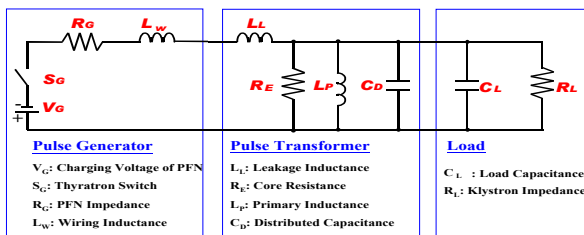


Fig. 1. Equivalent circuit of pulse generator system

Figure 1 shows the equivalent circuit of a pulse generator, step-up pulse transformer and load.^[1-3] By analyzing the behavior of each of simplified equivalent circuits for a given pulse width (τ) and load (R_L, C_L), transformer parameters such as primary inductance (L_P), leakage inductance (L_L), distributed capacitance (C_D) can be determined and thereby optimized for the best pulse response. These transformer parameters are a function of coil geometry and winding configuration, dielectric constant of the insulation, and the permeability of the core material.

B. Optimum waveform and rise time analysis

The pulse efficiency depends on the detailed design parameters of the pulsing system including a pulse transformer and a load. We can neglect the effect of the shunt resistance R_e and the shunt inductance L_P during the short rise time in the leading edge analysis.

The normalized load voltage $y(t)$ defined as

$$y(t) = \frac{V_L(t)}{V_G} \left\{ \frac{1+m}{m} \right\} \tag{1}$$

is given by

$$y(t) = \left\{ 1 - e^{-at} \left(\frac{a}{\omega} \sin \omega t + \cos \omega t \right) \right\} \quad (\sigma < 1) \tag{2}$$

$$y(t) = \left\{ 1 - e^{-at} \left(\frac{a}{k} \sinh kt + \cosh kt \right) \right\} \quad (\sigma \geq 1) \tag{3}$$

where

$$a = \frac{2\pi\sigma}{\tau}, \quad k = \frac{2\pi\sqrt{\sigma^2-1}}{\tau}, \quad \omega = \frac{2\pi\sqrt{1-\sigma^2}}{\tau}$$

$$\sigma = \frac{1}{2\pi\sqrt{m(m+1)}} \left\{ \sqrt{m} + \frac{1}{\sqrt{m}} \right\}, \quad \tau = 2\pi\sqrt{\frac{m}{(m+1)}} \sqrt{L_T C_T}$$

$$m = \frac{R_L}{R_G}, \quad \sqrt{m} = \frac{Z_T}{R_L}, \quad Z_T = \sqrt{\frac{L_T}{C_T}}$$

$$L_T = L_W + L_L, \quad C_T = C_D + C_L$$

m : matching parameter between the generator and the load, and \sqrt{m} is the impedance matching parameter between the transformation system and the load, Z_T is the transformation impedance of the pulsing system.

The expanded view of the leading edge of $y(t)$ near the flat top is shown in figure 2 as a function of the damping factor σ . In this figure, the normalized time S is defined by $S = t/\tau$. For a given value of L_T and C_T , small σ gives fast rise time but generates large overshoot. For a matched load, the rise time is determined by

$$t_r = \sqrt{2} \pi S(\sigma) \sqrt{L_T C_T} \tag{4}$$

where, $S(\sigma)$ is a fitting function to give the rise time from 10% to 90% of maximum pulse height.

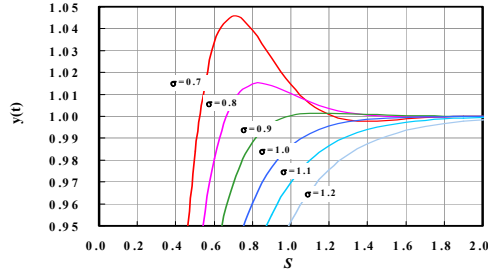


Fig. 2. Normalized rising-pulse waveform for various values of the damping factor

In general, a pulse flat-top with less than $\pm 0.5\%$ ripple is required to produce a high efficiency pulse. The damping factor σ has to be larger than 0.86 to limit the overshoot to less than 0.5% during the flat-top.^[4] From the above analysis, a fast rise time can be realized by reducing the number of secondary turns, but it produces larger pulse droop and core size. Thus, tradeoffs among these parameters is required to generate the optimum output pulse.^[5]

C. Pulse generator design

The pulsed-power generator has a pulse-forming network (PFN), a high-power pulse switch, and a step-up pulse transformer. The design procedure of a pulsed generator system is summarized in Fig. 3.

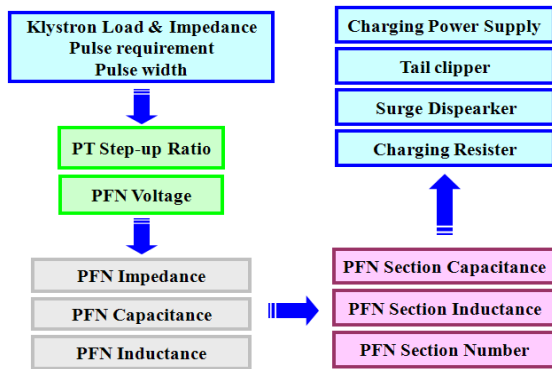


Fig. 3. Design procedure of a pulsed generator

The total capacitance of the PFN is given by the principle of energy-conservation. The energy stored in the PFN must be the same as the energy transferred to the load by a pulse:

$$\frac{1}{2} C_{PFN} V_{PFN}^2 = \int_0^{T_p} V_L I_L dt \quad (5)$$

or

$$C_{PFN} = \frac{2V_L I_L T_p}{V_{PFN}^2} \quad (6)$$

where

- C_{PFN} = the total PFN capacitance
- V_{PFN} = the charging voltage of the PFN
- T_p = the pulse width
- V_L = the load voltage
- I_L = the load current

The total inductance of the PFN, L_{PFN} , is given by the equation for the PFN characteristic impedance Z_{PFN} :

$$Z_{PFN} = \sqrt{\frac{L_{PFN}}{C_{PFN}}} \quad (7)$$

The number of sections of the PFN, N_{PFN} , is closely related to the pulse rise time and to the required flatness of the pulse top. In general, a larger section gives a faster rise time.

III. SYSTEM DESCRIPTION

The pulse generator with the high-voltage pulse transformer is used to drive a 30-MW klystron for a 10-MeV electron beam accelerator system. The main electrical circuit diagram and design parameters of the pulse generator are shown in Fig. 4. Main components of this system are composed of 15-stages of PFN, thyatron tube switch (E2V, CX2412X), 1:13 step-up pulse transformer.

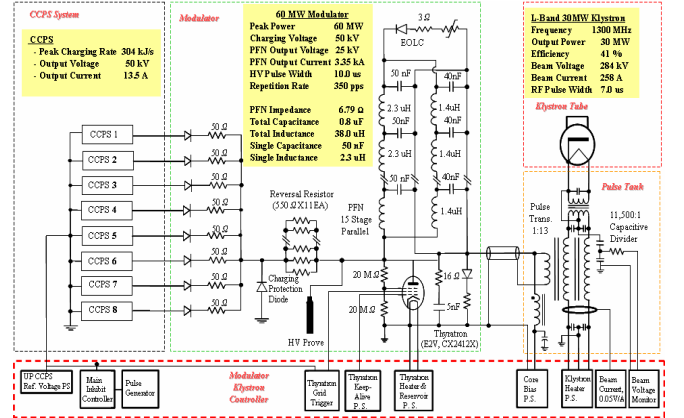


Fig. 4. Schematic circuit diagram of a pulse generator

In this system, the pulse energy is initially stored in an artificial delay-line PFN and then periodically discharged into the primary of the pulse transformer by a thyatron switch. During the inter-pulse period, the PFN is recharged from the dc supply.

IV. EXPERIMENTAL RESULTS

A. High voltage test

The high-voltage performance test was performed with a klystron (TV2022D S/N: 23187) to measure the pulse characteristics of the pulse generator by using the circuit layout as shown by Fig. 4. In the circuit, the PFN capacitor was charged to a voltage of 42 kV by using a high-voltage inverter power supply. Initially, the pulse modulator was tested with a 6.51 Ω resistive matching load, which is equivalent to klystron impedance referred to the primary of the pulse transformer. By tuning the PFN inductance, the output voltage of the pulse modulator was set to the desired rise-time and flat-topped pulse. The final test conditions and results for high-voltage performance measurement are summarized in Table 1.

Table 1. HV test conditions and results

Test Parameters	Values
Klystron load	1.1 k Ω
PFN charging voltage	42 kV
Load beam voltage (V_B)	276.58 kV
Load beam current (I_B)	246.4 A
Pulse width@70% (T_p)	9.3 μ s
CVD ratio	11,500
CT ratio	0.05 V/A

Figure 6 shows a set of displays of the final-load voltage and the corresponding current. As a result, the high voltage pulse with a rise time of $0.85 \mu\text{s}$ (10-90%) was successfully generated up to 277 kV at a frequency of 10 Hz. The pulse width of the output voltage is $9.3 \mu\text{s}$ with a flat-top of $6.5 \mu\text{s}$ and a flatness of 1.3%. From the measured waveform analysis for klystron, the measured rise time is confirmed as $1.4 \mu\text{s}$ (0-99%) with an overshoot of 2%, and the pulse droop approximately 2.7%.

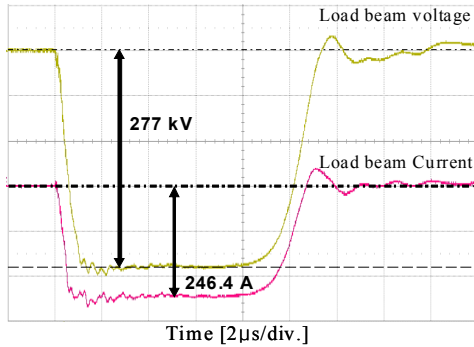


Fig. 6. Output voltage (11,500X) and current (20X) waveform with the klystron

From the measurement data using the klystron, we can find the differences both overshoot of 1.5% and voltage droop of 0.3% with the design. In this test, the PFN inductance was not adjusted to tune a flat-top and optimize the output waveform. Subsequent experimentation is needed to accomplish this. The droop can be compensated by PFN tuning. The large overshoot can be reduced by tuning the damping factor σ with wiring inductance.

B. Simulation and discussion

To investigate the parameter value to be matched with measured result, the simulation method was used to analyze the behavior of the equivalent circuit model. Fig. 7 shows the simulation circuit and parameters of the pulsed modulator system using the Psim 7.05 code.

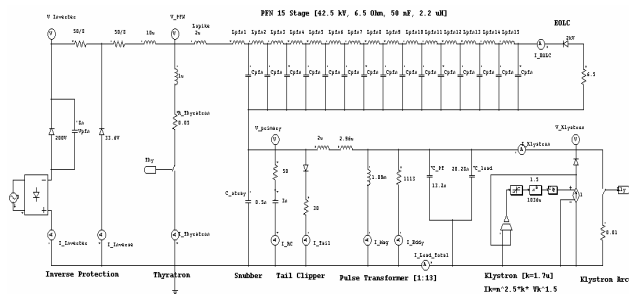
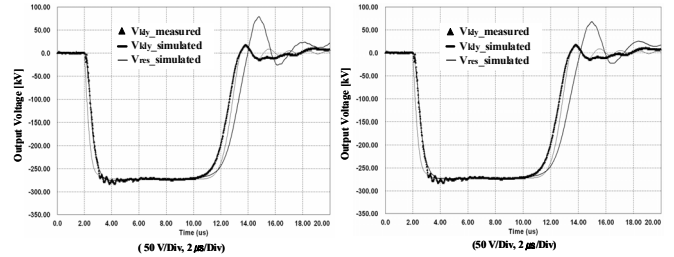


Fig. 7. Simulation circuit of the modulator system

After assigning all the known parameters and estimating values for the devices, the PFN inductors are tuned to generate an optimum pulse output. The characteristics test results of the pulse system were compared with those of a simulated circuit, and the both results were found to be in agreement. Figure 8 presents the tested and simulated waveforms for the klystron cathode voltage. In both (a) and (b), the triangle curve ($V_{kly_measured}$) is the measured waveform and the thinner curve ($V_{res_simulated}$) is the simulated waveform for a resistive load of 6.51Ω without PFN tuning at $2 \mu\text{H}$. The simulated waveform for a resistive load gives the even flat-top width without overshoot, but the measured waveform shows an overshoot of approximately 2%.



(a) Wiring induct. : $2 \mu\text{H}$ (b) Wiring induct. : $2.6 \mu\text{H}$
Fig. 8. Tested and simulated voltage waveforms

Also, we investigated how the pulse transformer affects the pulse droop before and after transformer connection in simulation circuit. The pulse droop is approximately 2.71%, which can be compensated within 0.5% by PFN tuning.

Next, the PFN was tuned to fit the measured waveform and to identify the matched parameters for the klystron. The thinner curve ($V_{kly_simulated}$) (Fig. 8 a) shows the simulated result. We evaluated the effects of the overshoot while varying the wiring inductance. A tuning value of wiring inductance to give an overshoot of 0.5% of the system was then obtained by inspecting Fig. 8 b. The overshoot of 2% is caused by the small series inductance and can be reduced to within 0.5% by reducing the wiring inductance. The optimal tuning value was estimated in $2.6 \mu\text{H}$. The simulation results by the equivalent circuit model are in agreement with the measured data.

V. CONCLUSION

The high-voltage pulse generator system with less than $\pm 0.5\%$ ripple has been carefully designed and tested with 30-MW L-band klystron load.

The pulse rise characteristics are simplified and generalized for a high-power klystron. The damping factor σ must be $\sigma > 0.86$ for resistor load and $\sigma > 0.8$ for klystron to limit the overshoot to less than 0.5% during the flat-top phase. The assembled pulse system was studied through a parameter analysis and was successfully tested up to an output voltage of 277 kV for the 30-MW peak power klystron. The pulse width of the output voltage is $9.3 \mu\text{s}$ with a flat-top of $6.5 \mu\text{s}$ with a flatness of 1.3%. The designed pulse generator system is compared with simulation results. The optimal tuning parameter of the system was identified using the model simulation. The overshoot of 2% can be reduced to within 0.5% by tuning the wiring inductance to $2.6 \mu\text{H}$. Consequently, the wiring inductance, leakage inductance, and distributed capacitance should be made as small as possible to get a fast rise time. The optimum output pulse voltage can be accomplished by tuning the wiring inductance and PFN inductance of pulse system.

VI. REFERENCES

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