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장성덕, 강흥식, 박성주, 한영진, 조무현, 남궁원
포항공과대학교 가속기연구소

Design Optimization of High-Voltage Pulse Transformer for High-Power Pulsed Application

S. D. Jang, H. S. Kang, S. J. Park, Y. J. Han, M. H. Cho, and W. Namkung

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 pulse transformer is one of main determinants on the output pulse voltage shape. The pulse transformer was investigated and analyzed with the pulse response characteristics using a simplified equivalent circuit model. The damping factor σ must be >0.86 to limit the overshoot to less than 0.5% during the flat-top phase. The low leakage inductance and distributed capacitance are often limiting factors to obtain a fast rise time. These parameters are largely controlled by the physical geometry and winding configuration of the transformer. A rise time can be improved by reducing the number of turns, but it produces larger pulse droop and requires a larger core size. By tradeoffs among these parameters, the high-voltage pulse transformer with a pulse width of 10 ㎲, a rise time of 0.84 ㎲, and a pulse droop of 2.9% has been designed and fabricated to drive a klystron which has an output voltage of 284 kV, 30-MW peak and 60-kW average RF output power. This paper describes design optimization of a high-voltage pulse transformer for high-power pulsed applications. The experimental results were analyzed and compared with the design. The design and optimal tuning parameter of the system was identified using the model simulation.

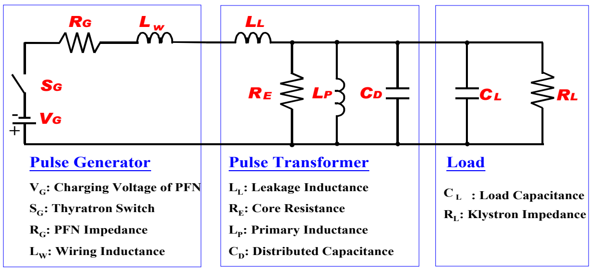
I. INTRODUCTION

A higher voltage pulse transformer is widely used in pulsed power circuits for applications such as accelerators, radar, medical radiation, or ionization systems. For an industrial applications of electron linear accelerator system, a line-type pulsed modulator is required to drive a high-power klystron as a pulsed RF source amplifier. This modulator often uses a step-up pulse transformer for generating high voltage output. The pulse transformer is a main determinant of the shape of the output voltage pulse. a high-voltage pulse transformer with a pulse width of 10 ㎲, a rise time of 0.84 ㎲, 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. Its primary functions are to match the impedances of a load to a source and to provide step-up of the voltage. In this paper, the pulse rise characteristics of a pulse transformer are simplified and generalized for a high-power klystron. The practical limitations on the rise time are discussed. The experimental results obtained using the pulse transformer are analyzed and compared with the design.

II. DESIGN BACKGROUNDS

A. Equivalent circuit analysis

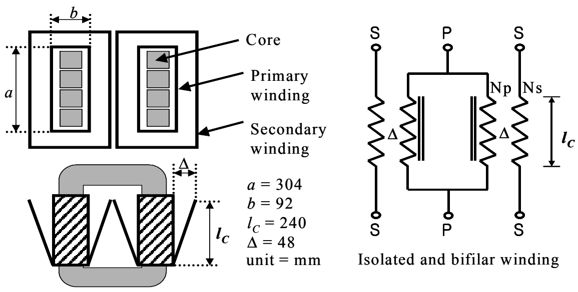
A pulse transformer and its associated pulse generator and load can be represented by an equivalent circuit. Figure 1 shows the equivalent circuit of a pulse generator, step-up pulse transformer and load.[1,2]



<Fig. 1> Equivalent circuit of pulse transformer

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 (Lp), 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. Figure 2 shows coil geometry and winding configuration of the pulse transformer.



<Fig. 2> Coil geometry and winding configuration

Transformer parameters such as shunt inductance (Lp), leakage inductance (L_L), distributed capacitance (C_D) are given by equation (1), (2), (3), respectively[2]. The best design is one having the lowest LC product, providing it has the proper L-C ratio to match.

$$L_L \simeq 2\pi U_c N_s^2 \left(\frac{\triangle_{12}}{l_c}\right) = 2\pi(a+b+4\triangle_{12}) N_s^2 \left(\frac{\triangle_{12}}{l_c}\right) [nH] \tag{1}$$

$$C_D \simeq \frac{1}{2}\left(\frac{8.854\epsilon_r U_c l_c}{\triangle_{12}}\right)^2 \left(\frac{n-1}{n}\right)^2 \quad [pF] \tag{2}$$

$$L_P \simeq 4\pi\mu_e N_p^2 \frac{A_e}{l_m} [nH] \tag{3}$$

where, N_p is the number of turns in the primary coil, △

is the insulation distance between layers, U_c is the average circumference of the layers in cm, l_c is the winding length in cm, ε_r is the relative dielectric constant of the insulating material between the layers, μ_e is the relative pulse permeability of the core, A_m is the cross-sectional area of the core, and l_m is the mean magnetic path length of the core, n is the step-up ratio.

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

$$y(t) = \frac{V_L(t)}{V_G}\left\{\frac{1+m}{m}\right\} \tag{4}$$

is given by

$$y\ (t)\ = \left\{1 - e^{-at}\left(\frac{a}{\omega}\sin\omega t + \cos\omega t\right)\right\}\quad (\sigma\ <\ 1) \tag{5}$$

$$y\ (t)\ = \left\{1 - e^{-at}\left(\frac{a}{k}\sinh kt + \cosh kt\right)\right\}\quad (\sigma\ \geq\ 1) \tag{6}$$

where

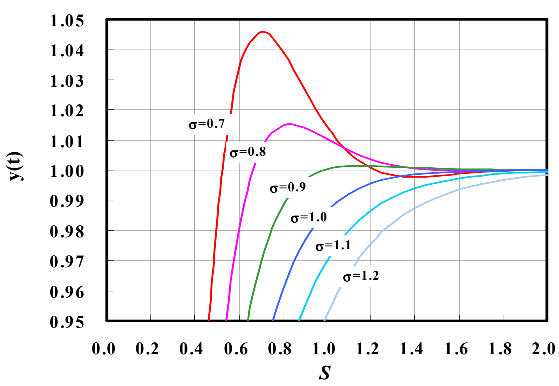
$$a = \frac{2\pi\sigma}{\tau},\quad k = \frac{2\pi\sqrt{\sigma^2 - 1}}{\tau},\quad \omega = \frac{2\pi\sqrt{1-\sigma^2}}{\tau}$$

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

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

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

m is the matching parameter between the generator and the load, and γ is the impedance matching parameter between the transformation system and the load, Z_T is the transformation impedance of the pulsing system.



<Fig. 3> Normalized rising-pulse waveform for various values of the damping factor

The expanded view of the leading edge of *y(t)* near the flat top is shown in figure 3 as a function of the damping factor σ. In this figure, the normalized time S is defined by $S = t/\tau$. The pulse shape and the rise time are sensitive to the damping factor σ near the flat top. 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

$$t_r = \sqrt{2}\ \pi\ S(\sigma)\sqrt{L_T C_T} \tag{7}$$

where, $S(\sigma)$ is a fitting function to give the rise time from 10% to 90% of maximum pulse height, In general, a pulse flat-top with less than ± 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.[3]

C. Droop and core size

The pulse magnetization of the core, droop, and core volume is given by (8), (9), (10), respectively.

$$V_s\ \tau_w = 10^{-8}\Delta B\ N_S\ A_e \tag{8}$$

$$D_r = \frac{R_L \tau_w}{2L_S} = \frac{\Delta B\ R_L\ l_m}{2\mu_0\ \mu_e\ V_S\ N_S} \tag{9}$$

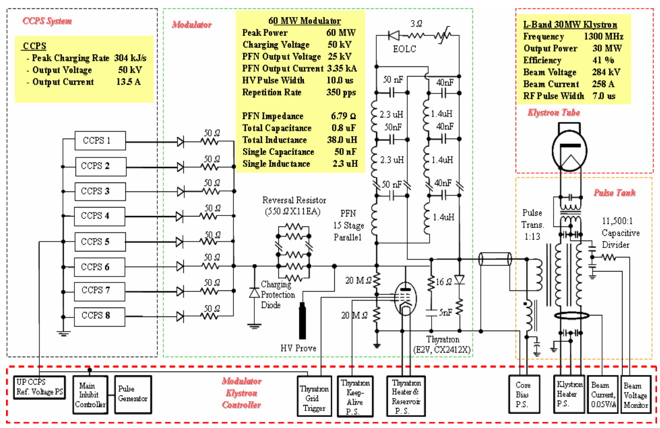
$$V_{CORE} = \frac{2\ \mu_0\ \mu_e}{\Delta B^2}\ P.\ \tau_w.\ D_r \tag{10}$$

where ΔB is the average increment of the magnetic flux density of the core in gauss, V_s is the load voltage in volts, and τ_w is the pulse width

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.[4]

III. SYSTEM DESCRIPTION

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



<Fig. 4> Schematic circuit diagram of a pulse modulator

In this system, the pulse energy is initially stored in an artificial delay-line pulse forming network (PFN) and then periodically discharged into the primary of the pulse transformer by a thyratron switch. During the inter-pulse period, the PFN is recharged from the dc supply. Pulse transformer also made it possible to match the impedance of the load to a power source for maximum transfer of energy from the modulator to a microwave electron tube.

In practice, a negative polarity pulse is applied to the klystron hot cathode. The isolated and secondary bifilar winding technique is used for voltage distribution of high voltage pulse transformer.[1][2] Heater power can be supplied to the cathode by means of a bifilar secondary winding of the pulse transformer.

<Fig. 5> Photograph of 1:13 pulse transformer

Figure 5 shows a photograph of the fabricated pulse transformer. It is composed of four cores, primary windings, secondary windings, and supporting structures. Each subcore is wound from a grain-oriented silicon steel sheet (0.05 mm thick., Microsil, "ML" cut core). The transformer is an isolation transformer type with two parallel primary basket windings and two parallel tapered secondary basket windings.

IV. DESIGN AND EXPERIMENTAL RESULTS

A. Design results

The transformer parameters are measured after the transformer assembled. Main designed and measured parameters of the pulse transformer are summarized in table 1.

<Table 1> Main parameters of a pulse transformer

Parameters	Designed	Tested
Turns ratio	13	12.82
Primary turns	6	6
Leakage inductance	2.4 μH	2.95
Distributed capacitance	66.9 pf	78.3 pf
Primary inductance	1.09 mH	0.58 mH
Droop	2.99 %	2.7 %
Overshoot	0.25 %	2 %
Magnetic flux swing	2.54 T	-
Effective core cross-section	143.5 ㎠	-
Mean magnetic path length	107 ㎝	-
Core weight	117 ㎏	-

The effective pulse permeability is a very important parameter to design pulse transformers. To estimate droop of load voltage, information regarding the primary inductance is needed; this is determined by the effective pulse permeability, core cross-section, magnetic path length and number of turns. The effective pulse permeability can be obtained using the load voltage droop. The designed effective pulse permeability of the cut core was selected as 1800 based on previous studies.[5][6] The leakage inductance is measured by LCR meter (Hioki 3532) connected across the primary with the secondary shorted and also calculated by equation (1).

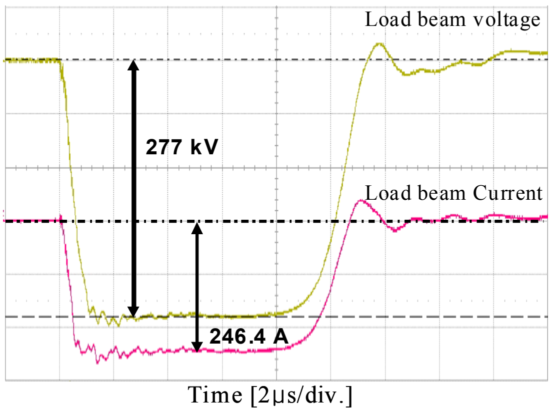
B. High voltage test

The high-voltage performance test was performed with a klystron (TV2022D S/N: 23187) to measure the pulse characteristics of the pulse transformer 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. Secondarily, the developed pulse transformer was tested for the klystron, which has a peak power of 30 MW and a pulse duration of 7 ㎲ as the RF source for the industrial linear accelerator system. The final test conditions and results for high-voltage performance measurement are shown in Table 2.

<Table 2> HV test conditions and results

Test Parameters	Values
Klystron load	1.1 kΩ
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 ㎲
CVD ratio	11,500
CT ratio	0.05 V/A

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

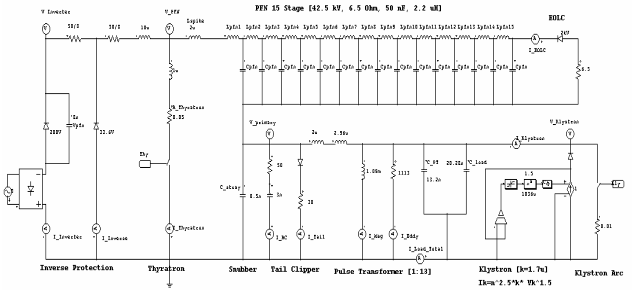


<Fig. 6> Output voltage (11,500X) and current (20X) waveform with the klystron

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.

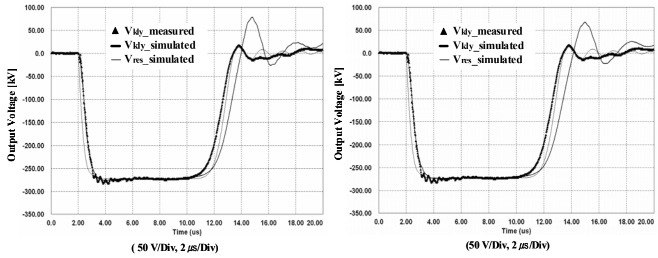
C. Simulation and discussion

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 transformer were compared with those of a simulated circuit, and the both results were found to be in agreement.



(a) Wiring induct. : 2 μH (b) Wiring induct. : 2.6 μH
<Fig. 8> Tested and simulated voltage waveforms

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 6.51 Ω without PFN tuning at 2 μH. The simulated waveform for a resistive load gives the even flat top and enough flat top width without overshoot, but the measured waveform shows an overshoot of approximately 2%. 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 (Vkly_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 μH. The simulation results by the equivalent circuit model are in agreement with the measured data.

V. CONCLUSION

An L-band industrial linear accelerator requires a flat-topped pulse with less than ± 0.5% ripple to meet the beam energy spread requirements and improve pulse efficiency of an RF system. The high-voltage pulse transformer design requires a custom and system-oriented design. The 1:13 high voltage pulse transformer has been carefully optimized and designed with klystron-modulator system requirements to drive a 30-MW L-band klystron load. The peak and average power capability are 71.3 MW (284 kV, 258 A, 285 pps at load side with 10 μs pulse width) and 203 kW, respectively.

In this paper, the pulse rise characteristics are simplified and generalized for a high-power klystron. A generalized rise-time chart is presented, which is a useful in finding the rise time as well as in predicting the pulse shape for a given pulse system. The damping factor σ must be σ >0.86 for resistor load and σ >0.8 for klystron to limit the overshoot to less than 0.5% during the flat-top phase. A rise time can be improved by reducing the number of turns, but this produces larger pulse droop and requires a larger core size. The assembled pulse transformer 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 μs with a flat-top of 6.5 μs with a flatness of 1.3%. The measured rise time is confirmed as 1.4 μs (0-99%) with an overshoot of 2%, and pulse droop is approximately 2.7%. The designed pulse transformer 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 μH. Consequently, the wiring inductance should be made as small as possible to get a fast rise time. If the wiring inductance is relatively large, a smaller leakage inductance and a larger distributed capacitance are required. The optimum output pulse voltage can be accomplished by tuning the wiring inductance and PFN inductance through optimum design of the pulse transformer.

VI. REFERENCES

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