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DEVELOPMENT OF THE PULSE TRANSFORMER FOR NLC KLYSTRON PULSE MODULATOR*

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Abstract

We have studied a conventional pulse transformer for the NLC klystron pulse modulator. The transformer has been analyzed using a simplified lumped circuit model. It is found that a fast rise time requires low leakage inductance and low distributed capacitance and can be realized by reducing the number of secondary turns, but it produces larger pulse droop and core size. After making a tradeoff among these parameters carefully, a conventional pulse transformer with a rise time of 250ns and a pulse droop of 3.6% has been designed and built. The transmission characteristics and pulse time-response were measured. The data were compared with the model. The agreement with the model was good when the measured values were used in the model simulation. The results of the high voltage tests are also presented.

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Abstract

We have studied a conventional pulse transformer for the NLC klystron pulse modulator. The transformer has been analyzed using a simplified lumped circuit model. It is found that a fast rise time requires low leakage inductance and low distributed capacitance and can be realized by reducing the number of secondary turns, but it produces larger pulse droop and core size. After making a tradeoff among these parameters carefully, a conventional pulse transformer with a rise time of 250ns and a pulse droop of 3.6% has been designed and built. The transmission characteristics and pulse time-response were measured. The data were compared with the model. The agreement with the model was good when the measured values were used in the model simulation. The results of the high voltage tests are also presented.

1 INTRODUCTION

The klystron pulse modulator for the Next Linear Collider(NLC) requires to produce a 500kV, 530A, 1.5μs flat top pulse to drive a pair of PPM-focused 75MW klystron[1]. The R&D of basic elements, a charging supply , a PFN, a thyratron switch tube and a pulse transformer for a prototype NLC modulator are being performed at SLAC[2].

The power efficiency of the modulator is extremely important. The effective output power of the modulator is the power of the flat-top portion of the high voltage output pulse. Since a pulse transformer is a major contributor to the waveform, the pulse transformer requires a fast rise time. In order to achieve a rise time that is less than 400ns, we have improved the design of a 14:1 pulse transformer by tradeoffs among the droop, the core size and the rise time. The test transformer has been built, and low and high voltage tests have been performed.

2 ANALYSIS OF THE PULSE TRANSFORMER

In order to simplify the analysis, we consider the simple geometrical arrangement with rectangular core. A single-layer secondary is wound over a one-layer primary and the distance between layers is constant[3].

2.1 Equivalent circuit

Figure 1 shows an equivalent circuit for the pulse transformer. The L_P is primary inductance, the L_S is secondary inductance, the L_L is leakage inductance, the C_D is distributed capacitance, the L_D is distributed leakage inductance. These circuit elements can be calculated from the geometrical constants of the transformer, dielectric constant of the insulation, and the permeability of the core material.

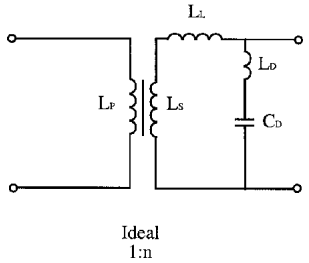

Figure 1. Equivalent circuit for the pulse transformer.

2.2 Droop and core size

The droop D_r is given by

$$D_r = \frac{R_{kly} \cdot \tau}{2L_s} ,$$

where R_{kly} is klystron impedance, τ the pulse width and L_S the secondary inductance.

The cross-section area of the core A is given by

$$A = \frac{V_s \tau}{\Delta B} \frac{1}{N_s} ,$$

where V_S is the voltage of secondary, N_S the number of secondary turns and ΔB the total magnetic flux density swing of the core. Thus, the cross-sectional area of the core is inversely to proportional to the number of secondary turns.

Since the secondary inductance L_S is calculated by

$$L_s = \frac{\mu_0 \mu_e A \cdot N_s^2}{l} ,$$

where μ_0 is the permeability of free space, μ_e the effective magnetic permeability, l the length of the magnetic path. Thus, the droop D_r is given by

$$D_r = \frac{\Delta B \cdot R_{kly}}{2\mu_0 \mu_e V_s} \frac{l}{N_s} .$$

The droop is propoportinal to the length of the magnetic path and inversely to proportional to the number of secondary turns.

2.3 Rise time

The rise time t_r is determined by

$$t_r \propto \sqrt{L_L \cdot C_D} .$$

The leakage inductance L_L is calculated by

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$$L_L \propto \frac{\mu_0 \Delta \cdot u \cdot N_s^2}{L} ,$$

where Δ is the distance between layers, u the average circumference of the layers and L the winding length.
The distributed capacitance C_D is calculated by

$$C_D \propto \frac{\varepsilon_0 \varepsilon_r u \cdot L}{\Delta} \left(\frac{n-1}{n}\right)^2 ,$$

where ε_0 is permittivity constant of free space, ε_r the dielectric constant of the insulation and n turn ratio. Therefore, from using $u \approx 4\sqrt{A} + \pi\Delta$, the rise time is given by

$$t_r \propto \sqrt{\varepsilon_r} \sqrt{\frac{V_s \cdot \tau}{\Delta B}} \sqrt{N_s} \frac{n-1}{n} .$$

It is found that the rise time strongly depends on the number of the secondary turns rather than turn ratio.

2.4 Tradeoffs

From the above analysis, it is found that a fast rise time requires low leakage inductance and low distributed capacitance and can be realized by reducing the number of secondary turns, but it produces larger pulse droop and core size. Thus, fast rise time and low droop are contrary to each other. Since a droop of several percentage can be compensated by making adjustments to the PFN, we can improve the rise time by tradeoffs among these parameters.

3 FABRICATION OF TEST PULSE TRANSFORMER

The conventional pulse transformer has been carefully optimized and designed by the model calculations. The transformer is an isolation transformer type with two parallel primary basket windings, and with two parallel tapered secondary basket windings as shown in Figure 2. It has been fabricated by Stangenes Industries, Inc.

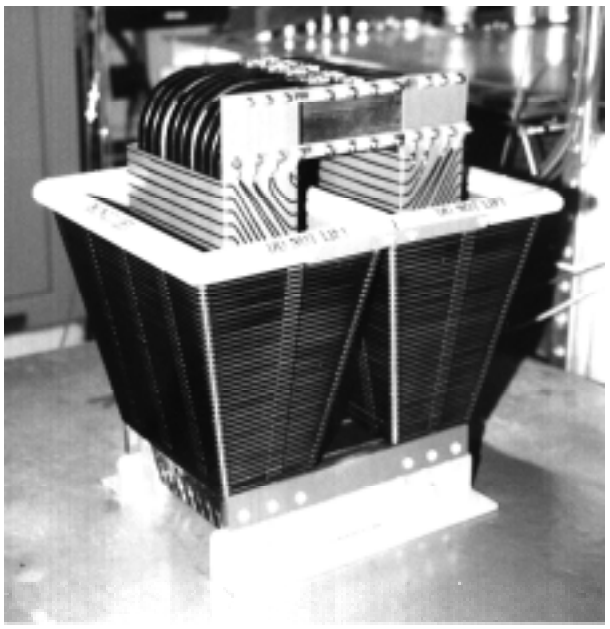

Figure 2. Side view of the pulse transformer.

Parallel primaries and secondaries are wound on each leg providing bifilar characteristics. The core is made up of 3 smaller subcores strapped together. Each subcore is wound from 0.002-inches thick, silectron grain-oriented silicon steel ribbon. Table 1 and 2 shows specifications and parameters of the pulse transformer, respectively.

Table 1. Specification of the pulse transformer

Primary voltage	33.2 kV
Primary current	5320 A
Secondary voltage	465 kV
Secondary current	380 A
Output impedance	1224 Ω
Flat top pulse width	1.5 μs
Pulse droop	3.6 %
Rise time	250 ns
Turn ratio	1:14
Pulse repetition rate	180 pps

Table 2. Parameters of the pulse transformer

Parameters	unit	
Total magnetic flux density swing	T	2.0
Effective magnetic permeability		1,500
Core packing factor	%	89
Area of the core	m^2	0.0102
Distance between layers in the high-voltage side	mm	52
Distance between layers in the low-voltage side	mm	6
Mean magnetic-path length	m	1.04
Effective winding length	mm	260
Circumference of the primary layer in the low-voltage side	mm	538
Number of primary turns	turns	3
Number of secondary turns	turns	42

4 LOW VOLTAGE TEST[4]

4.1 Electrical parameters

The primary inductance, secondary inductance, leakage inductance and the distributed capacitance between the primary and the secondary windings were measured in air with a LCR meter (BK Precision 875A). In the model calculation, the shape of the tapered basket and distribution of voltage along the windings were considered. The measured and calculated values are summarized in Table 3. It should be note that the calculated value does not include the inductance of the shorting strap across the primary. If the shorting is 100nH, 19.6μH should be subtracted from measured value. We are investigating the discrepancy between the calculations and the measurements.

Table 3. Electrical parameters for the pulse transformer

Item	unit	Model calculated value	Measured value
Primary Inductance	μH	130	55.2
Secondary Inductance	mH	25.48	10.81
Distributed capacitance	pF	25	33
Leakage inductance	μH	80.36	122.2

4.2 Transmission characteristics

The transmission characteristics of the pulse transformer were measured in air with the network analyzer(HP 3577A). The test circuit is shown in Figure 3.

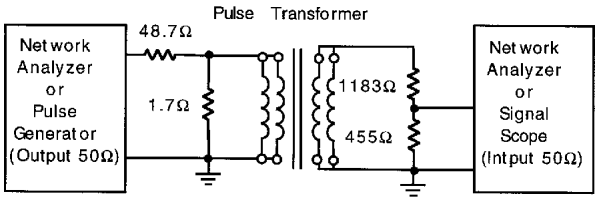

Figure 3. Test circuit.

Figure 4 shows the data of the amplitude and phase for the transformer as a function of frequency. A remarkable feature of the measurement data is a prominent sharp dip at 7.198MHz. This frequency corresponds to $1/2\pi\sqrt{L_D C_D}$. Therefore, the distributed inductance L_D is determined to be 14.8μH by using measured distributed capacitance. The broken curve in this figure shows result simulated by a computer code Micro-Cap IV using electrical parameters of the measured values. The simulation gives a good fit to the data.

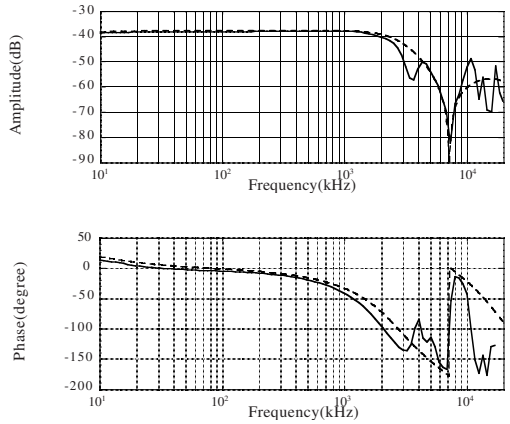

Figure 4. Amplitude and phase for the pulse transformer as a function of frequency.

4.3 Pulse response

A square low-voltage pulse signal with a width of 2μs was fed to the primary side, and the output pulse waveform was measured in air with the oscilloscope as shown in Figure 3. The result is shown in Figure 5. The rise time(10-90%) was 190ns. The broken curve in this figure shows simulated result. The simulation gives a good fit to the data.

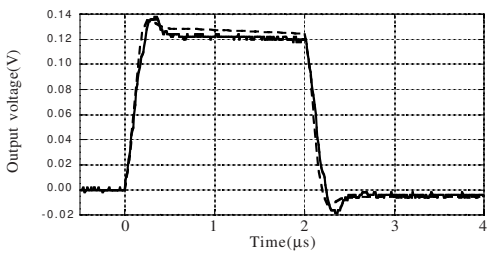

Figure 5. Pulse response of the pulse transformer.

5 HIGH VOLTAGE TEST IN OIL

The high voltage test of the pulse transformer connected to a 5045 klystron has performed. The transformer was installed in the Test Stand 3 modulator oil tank. Figure 6 shows an example of the klystron voltage waveform. The PFN was not adjusted to make a flat-top. A high voltage pulse with a rise time of 380ns(10-90%) was successfully generated. The broken curve in this figure shows simulated result. In this case, a total of distributed capacitance included klystron and tank was estimated to be 250pF.

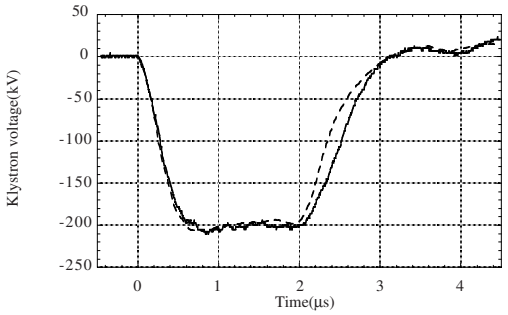

Figure 6. Output pulse waveform at the klystron.

6 SUMMARY

For the NLC klystron pulse modulator, we have improved pulse transformer design of 14 to 1 ratio by tradeoffs among the droop, the core size and the rise time. In the high voltage test of the transformer using a klystron load, a rise time of 380ns was successfully generated. The data calculated by the lumped circuit model are in agreement with the measured data. The model can also be used to optimize the design further.

7 ACKNOWLEDGEMENTS

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