DESIGN OF A PFN FOR THE NLC KLYSTRON PULSE MODULATOR

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Abstract

A pulse-forming network(PFN) with mutual coupling has been designed and built for the klystron pulse modulator of the SLAC Next Linear Collider(NLC). The PFN consists of a single-layer air-core coil with mutual coupling between sections and equal valued capacitors. The optimization of the coupling coefficient and the design of the air-core coil such as its radius, the number of turns and its total length are discussed. The results of the high and low voltage tests are also presented.

1 INTRODUCTION

The klystron pulse modulator for the NLC requires to produce a 500kV, 530A, 1.5µs flat-top pulse to drive a pair of PPM-focused 75MW klystron[1]. The modulator consists of parallel PFN's, a pulse transformer with a turns ratio of 1:14 and one thyratron. We are optimizing this design for energy efficiency, simplicity of manufacture, ease of servicing, and minimal cost[2].

The PFN is to be the subject of much R&D. A conventional PFN usually consists of the lumped-constant network which is made up of cascaded low-pass LC-filters. This conventional network produces gently-sloping waveform of the trailing edge of the output pulse due to the non-linear phase characteristic of the network. However, a PFN with mutual inductance, which is called the Guillemin type E network[3], enables us to improve the phase characteristic of the network and produces a better approximation to the rectangular pulse than does the conventional network, for the same number of elements. Moreover, the structure of the PFN of this type is very simple and easy to construct. The design and construction of a prototype of the NLC modulator PFN will be discussed, as well as computer simulation and experimental results.

2 DESIGN

2.1 PFN parameters

Figure 1 shows an equivalent circuit for the PFN with mutual coupling. The L is inductance, the L_C is residual inductance of capacitor, the C is capacitance, the M is mutual inductance between the series inductances, and the R is resistance load.

By employing the well-known techniques of conventional filter theory, the pulse width τ of the PFN is given by

$$\tau = 2n\sqrt{1+2k}\,\sqrt{CL}\,, \qquad (1)$$

where the n is the number of sections and the k(=M/L) is the coupling coefficient.
The characteristic impedance Z_0 of the PFN for low frequency is given by

$$Z_0 = \sqrt{1+2k}\sqrt{\frac{L}{C}}\,. \qquad (2)$$

The section inductance L and capacitance C are given by

$$L = \frac{\tau \cdot Z_0}{2n(1+2k)} \qquad (3)$$

and

$$C = \frac{\tau}{2nZ_0}\,. \qquad (4)$$

For specified values of Z_0, τ, n and k, Equations (3) and (4) give L and C. It should be noted that the nominal PFN is special case of these general equations with k=0.

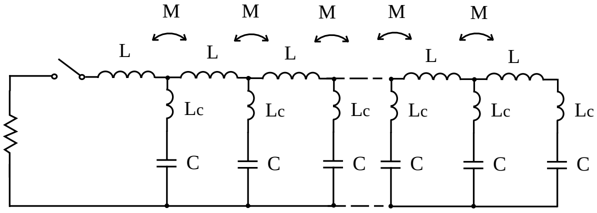

Figure 1: Equivalent circuit for the PFN with mutual inductance between adjacent coils.

2.2 Air core inductor

A single-layer solenoid is used as a PFN inductor and the coil radius and length of winding are chosen so as to give the required value of the coefficient of coupling.

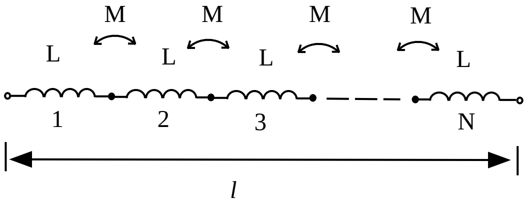

Figure 2: N coupled coils in series.

Figure 2 shows the N coupled coils in series. The coupling coefficient k is given by

$$k = \frac{M}{L} = \frac{L_t - N \cdot L}{2L(N-1)}, \qquad (5)$$

where L_t is the inductance of the total coils in series.

The coil inductance is calculated by the following approximate formula:

$$L_0 = \frac{r^2 n^2}{9r + 10l}\,[\mu\mathrm{H}], \qquad (6)$$

where r is the radius of the coil, n the number of turns and *l* its length in inches. This formula is accurate to within one per cent for *l*>0.8r, i.e., if the coil is not too short.

Using Equations (5) and (6), the radius r of the coil as a function of n is given by

$$r(n) = \frac{L}{n^2}\left\{9 + \frac{9}{2N}\left(\frac{N}{k} - 2\right)\right\}[\text{inches}]. \qquad (7)$$

The total length *l* of the coil is also given by

$$l(n) = \frac{9}{20}\frac{L}{n^2}\left\{9\left(\frac{N}{k} - 2\right) + \frac{9}{2N}\left(\frac{N}{k} - 2\right)^2\right\}[\text{inches}]. \qquad (8)$$

2.3 Calculations

As a prototype of the NLC modulator PFN, we have designed with the parameter values given in Table 1.

Table 1 Specification of the PFN

Number of parallel PFN	3
Total PFN impedance	5.6Ω
Number of sections(n)	11
PFN impedance(Z_0)	16.7Ω
Coupling coefficient(k)	0.21
Pulse width(τ)	2μs

From Equations (3) and (4), the L is 1.07μH and the C is 5.4nF. Using Equations (7) and (8), the radius r and the total length *l* of the coil are calculated as a function of the number of turns n per section. The results are shown in Table 2.

Table 2 Results of the calculation

Number of turns per section	Radius of coil (inches)	Total length of coil (inches)
2	7.9	177.4
3	3.5	79.7
4	2.0	44.9
5	1.3	28.7
6	0.9	19.9

Considering the physical size and its ability to withstand voltage in oil, the size of the coil is determined. The parameter values of n=4, r=2.0 and *l*=44.9 were chosen.

3 CONSTRUCTION

The three parallel PFN's were constructed based on the results of the calculation. Each PFN is made up of a continuous solenoid and eleven capacitor sections of 5nF each, which are mounted on a 48" length of aluminum base plate. The solenoid is wound with 44 turns on a 4" diameter with 3/8" copper tubing. The section capacitor consists of two low inductance glass capacitors which are placed in series to get 80 kV. These capacitors have a standard value of 10nF and a rated voltage of 40kV. The dimensions of the single capacitor are approximately 4 inches in diameter and 0.9 inches in thickness. Figure 3 is photograph of the PFN.

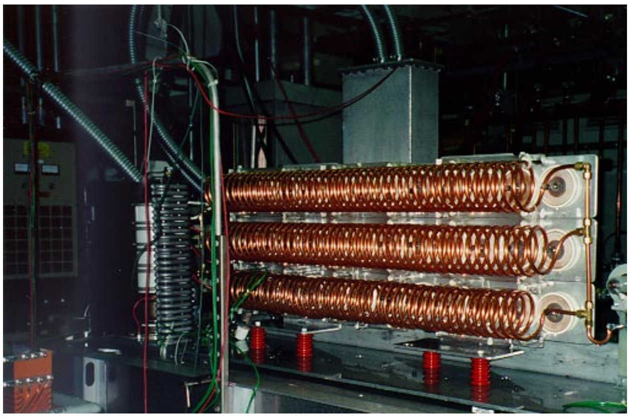

Figure 3: Side view of the three parallel PFN's.

4 TESTS AND RESULTS

4.1 Low-voltage test

In order to investigate a characteristic of the PFN, the low-voltage test of the three parallel PFN's was performed in air. The output of the PFN's was connected to a 6.6Ω load resistor via a MOSFET IRF 640 switch. The output pulse waveform was obtained for a charging voltage of 100V. The solid line in Figure 4 shows the result. The 10%-90% rise time was 100ns and the 90%-10% fall time was 500ns. The rise time is a sufficiently short because the rise time of the requirement is less than 400ns. The broken curve in this figure shows result simulated by a computer code Micro-Cap IV. The simulation gives a good fit to the measured data.

The most characteristic feature of the output waveform is that there is ripple in the trailing edge of the pulse. The coupling coefficient k strongly affects the behavior of the waveform of the trailing edge of the pulse. The optimum value of k, which corresponds to minimizing the phase distortion of the network and maximizing the flat-top length of the pulse, depends on the value of the residual inductance L_C of the section capacitor. If the L_C is assumed to be 20nH, the optimum value of k is 0.12[4]. In the case of this PFN, the ripple, therefore appears at the trailing edge of the pulse since the value of k is rather larger than optimum value.

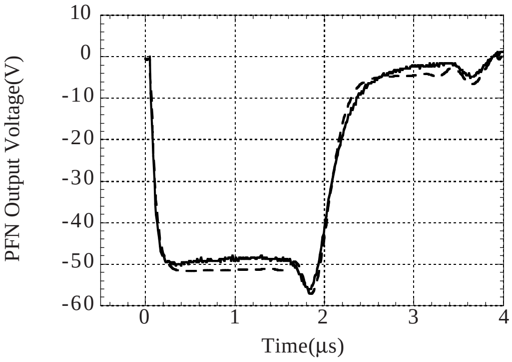

Figure 4: Output pulse waveform at the resistor load.

4.2 High-voltage test

The high-voltage test of the PFN has performed in the Klystron Test Lab. at SLAC to investigate the performance of the PFN under full system. A circuit diagram of the test modulator shows in Figure 5. The modulator consists of a conventional 1:14 pulse transformer[5], a thyratron switch tube and the PFN's which are all housed in an oil tank which also mounts a 5045 klystron. The heater current of the klystron was adjusted to match an impedance of the PFN with that of the klystron. To prevent an increase in pulse rise time, a triplate strip transmission line was used to connect the PFN's with the pulse transformer.

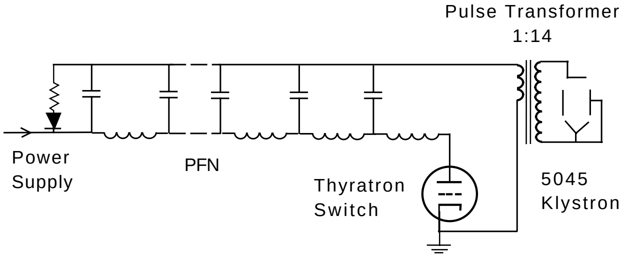

Figure 5: Circuit diagram of the high-voltage test.

The solid line in Figure 6 shows an example of the klystron voltage waveform. An output pulse with a peak voltage of 397kV, a rise time 300ns(10%-90%), a flat-top of 1.5μs(flatness ±5%) and a fall time of 500ns(10%-90%) was successfully generated. The flatness spec. of the pulse was not satisfied but the waveform of the pulse has enough flat-top to contain approximately 83% of the total pulse energy. The broken curve in this figure shows simulated result. The simulation gives a good fit to the measured data.

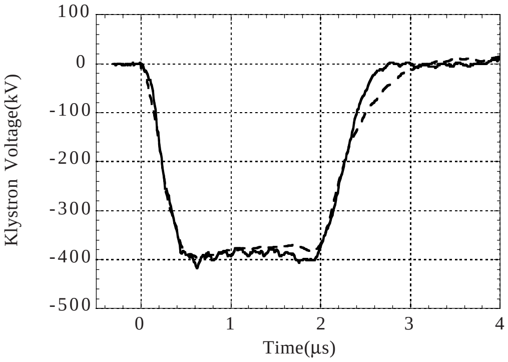

Figure 6: Output pulse waveform at the klystron.

5 CONCLUSIONS

A PFN with mutual inductance has been designed and constructed for the NLC klystron pulse modulator. From the results of the high and low voltage tests, we found that the PFN of this type produces excellent waveform with a wide flat-top and it improves the energy efficiency. The experimental results were well consistent with the simulated results. Future work will focus on the optimization of the number of sections for minimizing cost of the PFN.

6 ACKNOWLEDGEMENT

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