Design of Repetitive Very High Voltage Pulse Forming Networks of Short Duration

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ABSTRACT

Design of very high voltage pulse forming networks for short pulse (<1 µs) lengths often leads to a serious conflict between minimizing circuit inductance, component size, impedance, and insulation requirements. However, with the selection of the correct network configuration, one can minimize these conflicting parameters. Design of PFN's with unique shape and impedance characteristics has been investigated for over 50 years. Procedures are well established but represent only the ideal case for the circuit elements. Including the stray capacitances, inductances, and component equivalent circuits in the analysis, one often finds that the circuit designed on paper is not realized in practice. This often leads to "fine tuning" the circuit and modifications that can cost time and money. These problems are not experienced with networks of large impedances but increase as the impedance of the network decreases. This paper describes a computer aided procedure that allows the engineer to consider the effects of stray elements in the design of very high voltage (>1 MV) networks for low impedances, thus, minimizing any surprises when the circuit is constructed.

INTRODUCTION

Although most pulse forming networks are designed for square or trapezoidal pulse shapes, this approach may not be best suited for pulses of short duration and high voltages. Albeit the classical approach works fine from a theoretical standpoint, when non-ideal components are introduced into the system, the output pulse produced from this design procedure may not be ideal. Basing a network on a "non-ideal" response (or output) to account for component characteristics can result in achieving the desired response in actual circuit. The effects of component characteristics become more pronounced as the network impedance is decreased and as the operating voltage is increased. So, for a very high voltage and very low impedance networks, the designer is at the optimum of difficulty. The design procedure presented below is such a case.

For many pulse power applications, the load is excited by a rectangular shaped pulse. Typically, a flat top pulse with a square, trapezoidal or parabolic leading and trailing edge is used as a basis for designing the pulse forming energy storage network. Beginning with the most simplistic of pulse forming networks, the Guillemin Type 'C', and using a variety of mathematical operations, one can derive several different types of circuit configurations. For example, the impedance function for the Guillemin Type 'C'[1] network of Figure 1 is

$$Z(S) = \frac{\prod_{n=1}^{n} (L_n C_n S^2 + 1)}{\sum_{n=1}^{n} C_n S \prod_{m=1 \neq n}^{n} (L_m C_m S^2 + 1)} \qquad [1]$$

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where n = 1,3,5,7... and m = 1,3,5,... A partial fraction expansion of [1] results in the impedance function for the network of Figure 2. This configuration has been designated as a "Type A" pulse forming network[1]. The expansion is written as

$$Z_p(S) = \frac{A_o}{S} + \sum_{n=2}^{2n-2} \frac{A_n S}{B_n S^2 + 1} + A_{2n} S, \qquad [2]$$

where "n" equals the number of sections and the A_n's and B_n's are the poles and zeros of equation [2]. From [2] the elements of the network of Figure 2 are given by

$$C_f = C_N = \frac{1}{A_o}, \qquad [3a]$$

$$L_f = L_{2n} = A_{2n}, \qquad [3b]$$

$$L_n = A_n \text{ and,} \qquad [3c]$$

$$C_n = \frac{B_n}{A_n}. \qquad [3d]$$

The fundamental component for the Type 'A' network is formed by C_n and L_{2n}. The other elements are used to filter the fundamental shape[3]. One should note, that the pulse formed by the network is determined by the L_n's and C_n's of the impedance function for the Guillemin Type 'C' network, which are, proportional to the coefficients of the Fourier expansion of the pulse shape used to derive the network.

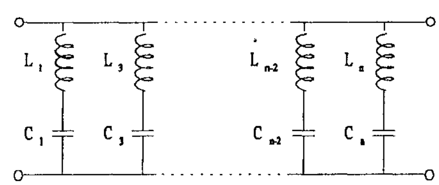

Figure 1. General Guillemin Type "C" network.

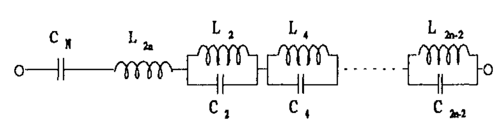

Figure 2. General Type "A" network.

The L's and C's for the Type 'C' network are found from the familiar relations[1]

$$L_n = \frac{Z_n \tau}{n \pi b_n} \qquad [4]$$

$$C_n = \frac{b_n \tau}{n \pi Z_n}. \qquad [5]$$

The Type 'A' network can be determined upon finding the b_n's, L's and C's from the above relations. First, the A_0 and A_{2n} terms are found from the following relations

$$A_0 = S\,Z(S)\big|_{S=0} \qquad [6]$$

$$A_{2n} = \lim_{S \to \infty} \frac{Z(S)}{S} \qquad [7]$$

The remaining A_n's and B_n's of Equation [2] are found by expanding Equations [1] and [2] and setting like terms equal to one another. This procedure is best explained with the following example.

DESIGN EXAMPLE

The following example steps through the design of a PFN with the following parameters.

Charge Voltage	1 MV
Load Resistance	100 Ω
Repetition Rate	100 Hz
Pulse Width	500 ns
Rise Time	150 ns
Fall Time	250 ns
Switch Voltage	100 kV
Shot Lifetime	10^9

The storage capacitor of the Type 'A' pulse forming network is placed on the primary of a 1:10 transformer in order to meet the switching requirements. Filtering or shaping sections are connected to the secondary of the transformer. The leakage inductance of the transformer is used as the fundamental inductance of the PFN[4]. Two 100 kV thyratrons, each with its own energy storage capacitor, drives one of the two transformer primaries. This configuration was used as an inductance reducing technique. Figure 3 illustrates a proposed 3-stage network. By placing the shaping sections on the secondary of the transformer, the PFN is designed for an impedance of 100 ohms rather than the 1-ohm impedance which would be required on the primary side of the pulse transformer. The higher impedance is preferred because it requires more realistic values of shaping section inductance for the PFN.

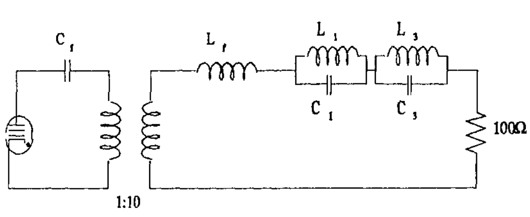

Figure 3. 3-stage Type 'A' network.

A 3-STAGE TYPE 'A' PFN

The first step in the design of the Type 'A' PFN is to decide on the desired pulse shape. Equation [4], [5], and [8] are used to calculate the values of the elements for the network shown in Figure 4. The b_n coefficient appearing in equations [4] and [5] is defined as

$$b_n = \frac{8}{n^2\pi^2}\sin\left(n\frac{\pi}{2}\right). \qquad [8]$$

Equation [8] is derived from a triangular shaped pulse used a a basis for the example network (more on this point later). The determination of the three stage Type 'A' PFN is then found

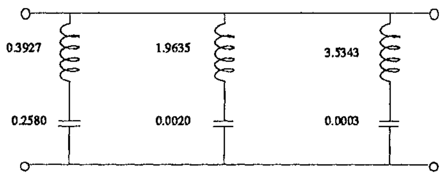

Figure 4. 3-stage Type "C" Guillemin network.

by writing the impedance function for the network shown in Figure 4 which from equation [1] yielded:

$$Z(S) = \frac{(L_1C_1S^2+1)(L_3C_3S^2+1)(L_5C_5S^2+1)}{SC_1(L_3C_3S^2+1)(L_5C_5S^2+1) + SC_3(L_1C_1S^2+1)(L_5C_5S^2+1) + SC_5(L_1C_1S^2+1)(L_3C_3S^2+1)} \qquad [9]$$

From equation [2] the partial fraction expansion is

$$Z_p(S) = \frac{A_0}{S} + \frac{A_2S}{B_2S^2+1} + \frac{A_4S}{B_4S^2+1} + A_6S. \qquad [10]$$

Rewriting equations [9] and [10] give

$$Z(S) = \frac{\dfrac{S^6(L_1C_1L_3C_3L_5C_5) + S^4(L_1C_1L_5C_5 + L_3C_3L_5C_5 + L_1C_1L_3C_3) + S^2(L_5C_5 + L_1C_1 + L_3C_3) + 1}{C_1+C_3+C_5}}{S^5\left(\dfrac{C_1C_3C_5(L_1L_3+L_1L_5+L_3L_5)}{C_1+C_3+C_5}\right) + S^3\left(\dfrac{C_1(L_3C_3+L_5C_5) + C_3(L_1C_1+L_5C_5) + C_5(L_1C_1+L_3C_3)}{C_1+C_3+C_5}\right) + S} \qquad [11]$$

and,

$$Z_p(S) = \frac{S^6\left(\dfrac{A_6B_2B_4}{A_0}\right) + S^4\left(\dfrac{A_6B_4+A_6B_2+A_2B_4+A_0B_2B_4}{A_0}\right) + S^2\left(\dfrac{A_6+A_2+A_4+A_0B_2+A_0B_4}{A_0}\right) + 1}{S^5B_2B_4 + S^3(B_2+B_4) + S} \qquad [12]$$

respectively. Setting the coefficients of equation [11] equal to the coefficients of equation [12] produces:

$$B_2B_4 = \frac{C_1L_3C_3L_5C_5 + C_3L_1C_1L_5C_5 + C_5L_1C_1L_3C_3}{C_1+C_3+C_5} \qquad [13]$$

$$B_2 + B_4 = \frac{C1(L_3C_3+L_5C_5) + C_3(L_1C_1+L_5C_5) + C_5(L_1C_1+L_3C_3)}{C_1+C_3+C_5} \qquad [14]$$

$$\frac{A_6B_4 + A_6B_2 + A_2B_4 + A_4B_2 + A_0B_2B_4}{A_0} = L_1C_1L_5C_5 + L_3C_3L_5C_5 + L_1C_1C_3 \qquad [15]$$

$$\frac{A_6 + A_2 + A_4 + A_0B_2 + A_0B_4}{A_0} = L_1C_1 + L_3C_3 + L_5C_5. \qquad [16]$$

The fundamental components are found using equations [6] and [7] respectively as:

$$A_0 = \frac{1}{C_1 + C_3 + C_5} \qquad [17]$$

$$A_6 = \frac{L_1L_3L_5}{L_1L_3 + L_1L_5 + L_3L_5} \qquad [18]$$

Equations [13] through [16] are then solved for the unknown constants B_2, B_4, A_2 and A_4. Once the constants are determined, the *L's* and *C's* are calculated with Equation [3]. Figure 5 shows the final normalized Type 'A' circuit.

In the example case, preliminary calculations revealed that the risetime specification could not be achieved due to the inductance of the commercially available, off the shelf, high voltage components. Using the circuit configuration depicted in Figure 3, the effect of the transformers leakage inductance was minimized leaving only to deal with the inductive component of the energy storage capacitors. Several different pulse shapes were used to derive the circuit values, i.e. parabolic, exponential, square, trapezoidal, etc. All fell short of meeting the desired output pulse shape. Noting that the rise, fall and flat-top of the desired output pulse were comparable in value connoted basing the network on a triangular shaped pulse. Accounting for the inductance in the connections and the energy storage capacitors, it was clear that the frequency response of the circuit would be limited well below the frequency components necessary to generate the apex (discontinuous function) of the triangle. Furthermore, the response of the circuit would be limited to such a degree that there would be no apex at all. So reasoning, if these frequencies are not available, the top of the triangle would be cut off, leaving a plateau, or in this case, the desired flat top. Similar results could be achieved for the rise and fall time by basing the network on a "sawtooth" pulse shape. However, one must know to some accuracy the values of the equivalent circuits describing the various components (i.e. equivalent series resistance, ESR, equivalent series inductance, ESL, etc). Knowing these values, it is a simple circuit calculation to determine the approximate frequency response of a one-loop circuit constructed of these components, thus allowing a choice of pulse shapes to base the desired network.

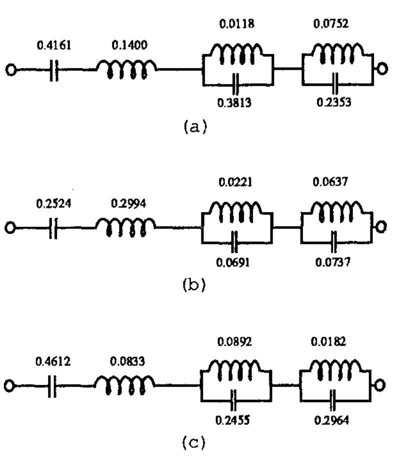

Figure 5. *Normalized Type 'A' networks for a Parabolic (a), Triangular (b), and a Square (c) pulse shape.*

COMPARISON WITH CLASSICAL METHOD

A comparison of the method presented here with the classical PFN design approach gives insight on when this method might be applied and the results that one should expect. The different pulse shapes considered are a parabolic, square, and triangular pulse. The values for the filtering sections were found using the normalized circuits of Figure 5. Table 1 gives the values of inductors and capacitors for the three types of pulse shapes mentioned. The values are for a pulse forming network with an impedance of 100 Ω and a pulse width of 400 ns.

The circuit used for modeling the ideal system is shown in Figure 3. The values of the network components are listed in Table 1. Figure 6 shows the output pulses produced by the three PFN's. It's apparent that for the "ideal case" the triangular wave form produces the worst pulse shape.

Table 1. Values of inductors and capacitors for the circuit of Figure 3.

Pulse Shpae	C_f (nF)	L_f (μH)	L_1 (μH)	C_1 (nF)	L_2 (μH)	C_2 (nF)
Parabolic	170	5.6	0.472	1.500	3.000	0.941
Square	180	3.3	3.600	0.982	0.728	1.200
Triangular	170	12.0	0.884	0.276	2.500	0.294

An equivalent series inductance (ESL) of 60 nH is added in series with each capacitor for the non-ideal case; furthermore, a transformer leakage inductance of 17 μH and a discharge loop inductance of 100 nH have been added to the circuit. Figure 7 shows the final network with the stray elements added. The outputs for the non-ideal case are shown in Figure 8. For the non-ideal case the best output pulse is obtained with the triangular pulse design parameters. The slow fall time is due to the increased inductance added by the loop and leakage inductance of the circuit. Remember that the fundamental component of the waveform is determined by the primary capacitance and the series inductance of the circuit. The leakage and loop inductance make up a series inductance which is almost twice the designed value and cannot be changed. The primary capacitance could be lowered to shorten the rise and fall time, but in doing so the peak voltage would drop to an unacceptable level.

CONCLUSION

The design method described can be carried out to produce a 3-stage Type 'A' PFN capable of producing any desired pulse shape. This is accomplished by changing the values of the elements in Figure 4 from those used to produce a flat top pulse with parabolic rise and fall, to the values representing the desired pulse shape, then solving equations [13] through [18] for the new values of A_0 ...A_4. Normalized circuits for more common pulse shapes are also shown in Figure 5[1].

In the ideal case, there is no advantage in using a triangular pulse shape. In fact, as seen in the wave forms of Figure 6, the classical square and parabolic designed pulse shapes produce pulses with a more desirable shape than those of the method presented here. However, when the PFN design requires a transformer with a large leakage inductance or a loop inductance which is much higher than can be tolerated by the network, the method presented in this paper has many advantages over the classical design approach.

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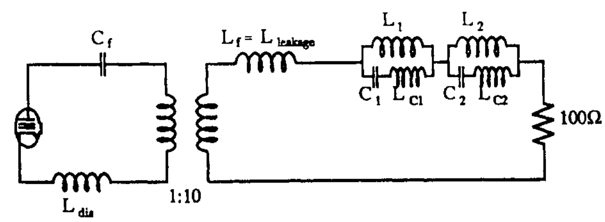

Figure 7. Non-ideal Type "A" circuit model.

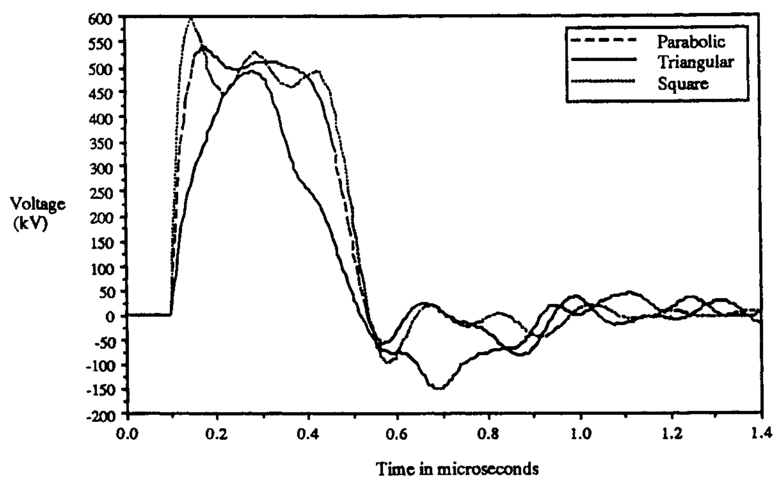

Figure 6. PFN outputs for ideal case.

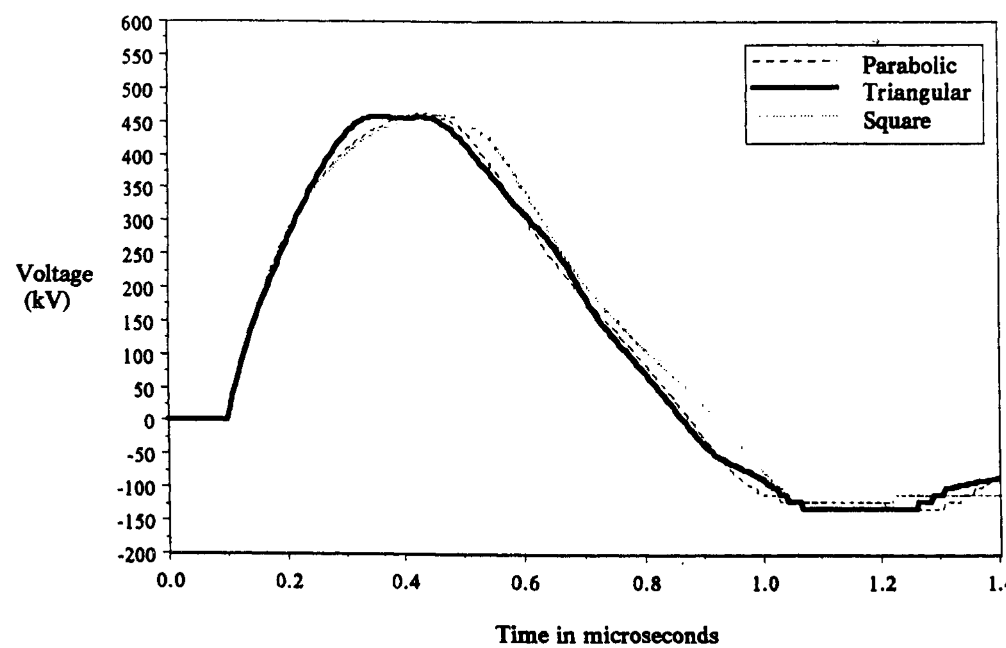

Figure 8. PFN outputs for the non-ideal case.