Optimisation of a transmission line transformer for megavolt nanosecond pulses

OPTIMISATION OF A TRANSMISSION LINE TRANSFORMER FOR MEGAVOLT NANOSECOND PULSES

*D.B. Pawelek, P.A.A.F. Wouters, A.J.M. Pemen, G.J.H. Brussaard, Ad Kemper
Eindhoven University of Technology, Department of Electrical Engineering, Department of Applied Physics P.O.Box 513, 5600MB Eindhoven, The Netherlands
E-mail: D.B.Pawelek@Tue.nl

Abstract

The area of pulsed-power technology covers a broad range of voltages and pulse durations. State of the art systems have voltages up to a few hundred kilovolts at pulse lengths down to the nanosecond range. Special applications require extreme field strengths in the range of 1 GV/m. The design of a compact source, meeting the above requirement aims for 1 MV, 1ns pulses.

In this paper, we propose a concept for a novel compact transmission line transformer for mega-volt nanosecond pulses avoiding the use of ferromagnetic cores around each individual transmission line. The proposed TLT consist of 10 coaxial transmission lines which are connected in parallel at the input and in series at the output.

One of the present challenges is the design of the connection to the input and output of the transmission line transformer.

INTRODUCTION

High-voltage pulse technology is widely used in applications ranging from radar to extreme ultra violet sources and from nuclear fusion to waste-water treatment. The proposed novel transmission line transformer aims for a major breakthrough in this technology. It will find application in science (lasers, plasma accelerators), in industry (there is an interest in the high-voltage system and for the associated diagnostic, behaviour of dielectric materials exposed to extremely short high-voltage pulses). The pulse source can be used as well for biomedical purposes (emitters of THz-radiation [1]) or processing of biomedical/-chemical materials by exposing them to short-pulsed high field strength [2] as in seismic profiling of deep-sea bottom layers [3].

This paper describes the design and construction of a compact transmission line transformer which can be used in the future for generating nanosecond MV pulses. The demand of compactness implies the use of very short pulses. The final aim of our project is to increase the performance of MV pulsed-power supplies to a level at which 1MV pulses can be produced with rise time, and jitter down to the 10-ps range. Our proposed device aims to improve these main aspects while avoiding ferromagnetic cores around each individual transmission line. This latter requirement should enable a more compact source design since the use of magnetic cores increases the necessary insulation distances.

THEORY OF TRANSMISSION LINE TRANSFORMERS

There are a number of transmission line transformer designs which can be used in pulsed power generators. Available TLT-related pulsed power circuit topologies are reviewed by Smith [4]. The simplest type of transmission line transformer has been chosen to fulfill the requirement for our compact construction. The proposed TLT consists of 10 coaxial transmission lines which are connected in parallel at the input and in series in the output. To explain its function, a model is used with four identical transmission lines, see "Fig. 1", but it can easily be extended to *n* lines.

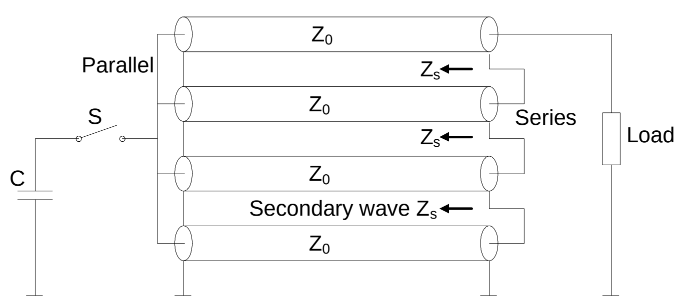

Fig. 1. The four stage TLT scheme

"Fig. 2" shows the schematic equivalent diagram of a four stage transmission line transformer. The output impedance, voltage and current are denoted as nZ_0, nV_0 and I_0 respectively, where I_0 is the switching current and Z_0 is the impedance of each transmission line. The secondary wave impedance Z_s in the design should be much larger than the characteristic impedance of each individual line.

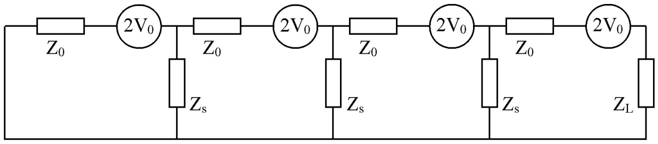

Fig. 2. Equivalent circuit diagram for the reflection at the end of four stages transmission line transformer

In an equivalent circuit diagram, each signal can be represented as a voltage source of twice the input voltage V_0 in series with the cable impedance Z_0. The load for each cable is the combination of the other cables, the actual load plus impedance for each cable that represents the return path for the wave that will propagate in the air between the braid and any other available conductor – it is called the secondary wave [5] (impedance Z_s in the equivalent circuit diagram).

Voltage in each line can be find by formula:

$$V_n = k_n (V_{n-1} + 2V_0) \qquad (1)$$

where

$$k_n = Z_n / (Z_n + Z_0) \qquad (2)$$

$$Z_n = Z_S (Z_{n+1} + Z_0) / (Z_S + Z_{n+1} + Z_0) \qquad (3)$$

Smith [4] and Wilson [6] use equivalent circuit presented on Fig. 3, from which the output voltage of the first step and the gain of an n-stage transformer can be estimated.

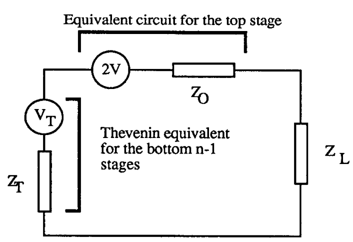

Fig. 3. Equivalent circuit diagram for determining the gain of an n-stage transmission line transformer

In this circuit the top stage is represented by a voltage source of amplitude $2V_0$ in series with the line impedance Z_0. The remaining (n-1) stages or lines are represented by a Thevenin equivalent circuit made up of a voltage source of amplitude V_T and impedance Z_T.

General expression for the output voltage of a transmission line transformer can be found by equation:

$$V_{out} = \frac{(2V_0 + V_T) \cdot Z_L}{Z_0 + Z_T + Z_L} \qquad (4)$$

where: $$V_T = \frac{4V_0 \cdot Z_S \cdot Q}{(B+1) \cdot Z_0} \qquad Z_T = \frac{2Z_S \cdot Q}{B+1} \qquad (5)$$

with: $$Q = \frac{1 - \left(\frac{B-1}{B+1}\right)^{2n-2}}{1 + \left(\frac{B-1}{B+1}\right)^{2n-1}} \qquad B = \sqrt{1 + 4 \cdot \frac{Z_S}{Z_0}}$$

NOVEL TRANSMISSION LINE TRANSFORMER

Fig. 4 presents a design of novel 10-stages transmission line transformer for megavolt nanosecond pulses.

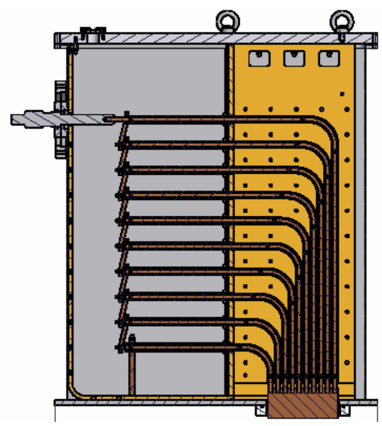

Fig. 4. Construction of novel transmission line transformer

The Wilson model discusses in the last section assumes that the connection point of the TLT has no dimension. However, for rise times shorter that 1ns the dimension of the TLT is unavoidably relatively large and transmission line effects along the connection points must be taken into account, see "Fig. 5".

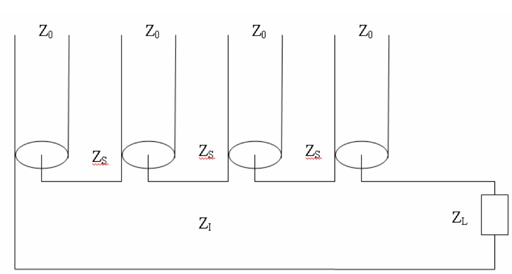

Fig. 5. The TLT scheme including transmission line effects along the connection points at the output

To simplify the analysis, lets assume that the secondary mode can be neglected. Each transmission line has impedance Z_0 ending with Z_I. If Z_I is much larger than Z_0 each TL can be modelled with a source of $2V_0$ owing to the nearly full reflection. The incoming pulse propagates in two opposite directions. Since the impedance to the left and right are taken equal the voltages are equal but have opposite polarities. The doubling of the voltages at the almost open output is lost by the separation of the pulses. On a longer time scale the pulse to the left reflects at the left side and returns with inversed polarity, so it adds to the direct pulse to the right. On the time scale we are interested in this is too late. Furthermore, the pulses coming from the transmission lines far from the load have losses due to reflection at each transmission line.

For cable number n=1…9, voltage in each line can be find by equation:

$$V_n = k\,(V_{n+1}+V_0) \tag{6}$$

where

$$k = 2Z_I \,/\, (2Z_I+Z_0) \tag{7}$$

The Output voltage can be found by equation:

$$V_{out} = 2\,(V_0+V_1) \tag{8}$$

or

$$V_{out} = 2\cdot V_0 \sum_{n=0}^{m-1} k^n = 2\cdot V_0 \frac{1-k^m}{1-k} \tag{9}$$

The behaviour of the complete TLT is more complicated, because:

- The connection between the line outputs is not simple transmission line configuration
- The secondary mode has to be included

Therefore a time domain electromagnetic field simulation with ST Microwave Studio is performed to analyze the performance of this ten stage TLT.

DESIGN OF TRANSMISSION LINE TRANSFORMER

The characteristic impedance of each coaxial line is given by

$$Z = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\frac{r_{ext}}{r_{int}} \tag{11}$$

with r_{ext}=*6.5mm* and r_{int}=*4.0mm*, and using vacuum as insulating medium between the two Ag conductors, Z_{line}=*24.3 Ω.*

At the output the lines are in series. The total impedance is simply the sum of the single line impedances. In contrast, at the input the reciprocal of the total impedance is the sum of the reciprocal of the impedances of each single line since they are in parallel.

Fig. 6. Transmission line transformer; the dimensions are: 635 mm long, 734 mm high and 350 mm wide

FINAL REMARKS

In this paper, the new transmission line transformer design is proposed and compared with existing model. The design was simulated using a time domain electromagnetic field solver – see Fig. 7. Input signal, individual signal at the output of each line and the total sum of outputs are shown.

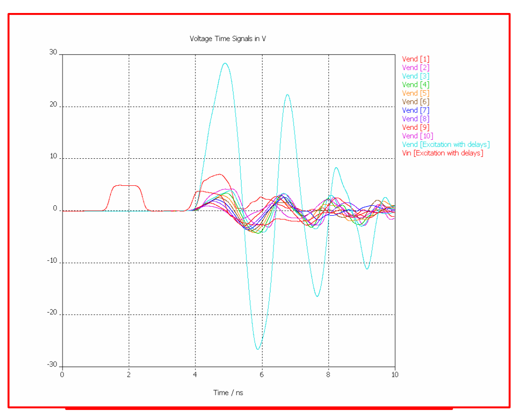

Fig. 7. Input and outputs voltages of each line of TLT

Using the model it is possible to improve the gain factor by changing some details of the TLT. As the gain is limited by the connection at the output, this port will be redesigned. An option is by step wise increasing the line impedance at each successive point where the next line enters.

A critical design aspect of the connection to the input and output of transmission line transformer is the synchronization of the pulses entering and leaving the 10 stages TLT. We plan both modelling and experiments on the input of transmission line transformer ($Z_{in} = 2\Omega$) in the near future. A disadvantage of a common pulse-forming line is that the voltage amplitude into a matched load is half of the applied voltage. The Blumlein circuit consisting of two lines can avoid this deficiency. Another option is using laser triggered capacitor discharge in order to inject synchronously pulses in all TLT lines.

At the output the pulse synchronization has to be realized through proper impedance matching and appropriate time delays in the individual transmission lines.

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