

# Energy Compression Based on Wound Transmission Lines Network for Pulsed Power Applications

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*Abstract* – In this paper, a method for energy compression is described in which regular storage elements are replaced by segments of transmission lines. The fundamental of this method is the direct proportion of the appearance time of a traveling voltage pulse on a channel to the electrical length of it. According to this fact, if power pulses are fed into a group of transmission lines of different lengths at proportional different times, they will reach the end points simultaneously and generate a higher output peak power, as a result of a rise either in voltage, current or a combination of both. This magnification is achieved by a suitable connection mode at the end points of the transmission lines. Main goal of this approach rather than its capability of operation in extremely high frequencies with short rise and fall times of rectangular pulses, is that the switching elements in the system need to tolerate a much lower peak power than the compressed power reached to the load. Another main aspect that is taken into consideration is the presence of the shield cable impedance contributing to the lines power loss. The very well known method used for minimizing these losses is winding the transmission lines to increase the line shielding inductance if coaxial cables are used. Therefore, herein, circuit models are presented to assess theoretically the temporal response of the wound coaxial pulsers by using SPICE circuit simulator.

*Key-words:* Wound Transmission Lines, Energy Compression, Pulse Generation, Pulsed Power, PFL

## 1 Introduction

Pulsed power generators made of lengths of transmission lines have been built in the 1970-2000 era at many laboratories around the world using very diverse schemes with coaxial lines or parallel plates driven by single or multiple switches for many different applications [1]. Some loads such as electric arcs, high power laser tubes operated in pulse mode, and high power flashbulbs used for photon excitation, require higher power than the source is able to supply. However, this power demand appears for relatively short intervals. In such cases, energy compression is required [2]. The principle of all energy compression methods is based on storage elements, which are charged for long periods, under low power conditions then discharged in relatively short time at high power rates. The storage elements commonly used are either capacitors or inductors. The circuits commonly used for energy compression incorporate switching elements, part of which has to tolerate high power rates usually at the output. The method for energy compression described in this paper resembles in a way pulse forming networks (PFN) techniques like those presented in [3]. The proposed method

incorporates transmission lines as storage elements. The energy is stored partially in electric field of propagating wave. Groups of transmission lines are charged, sequentially, by a source, which continuously supplies low power. Due to the natural features of transmission lines, they can be discharged simultaneously. The discharge is initiated naturally at the instance at which the propagating waves reach the end points of transmission lines, thus high rated power switches are omitted.

In voltage magnification condition, because of the physical construction of the device, the existence of parasitic short-circuit transmission lines, between the outer conductor of the coaxial cables and the ground plane, or inductive short-circuit paths to ground, can cause serious power loss as the number of stacked lines is increased. To avoid this problem and also to obtain a low pulse droop rate, all the cables in the stack, except the bottom one, can be wound inductively with or without the use of magnetic cores. In this analysis, the cables are considered to be sufficiently apart from each other to avoid isolation problems and to make negligible the effect of mutual inductance between them [4].

## 2 Principle of Operation

In the method proposed in this paper, advantage is taken of the spatial delay of waves propagating in transmission lines. Pulses propagating in a group of transmission lines are synchronized to reach the end points simultaneously and sum up across the load. In The case of passive load, high power switches in the load circuit are completely omitted. The preliminary idea has been reported in [5]. Consider a load  $Z_l$  is linked to a pulse source  $v_s(t)$  via a transmission line as shown in Fig. 1.

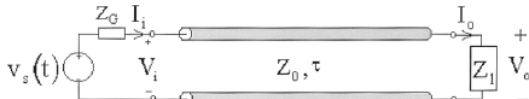


Fig. 1. Transmission line linking a source and a load

Without losing generality, it is assumed that the generator output impedance is 0. The input/output characteristics, for the time interval  $0 \leq t < 2\tau$  are given by

$$\begin{cases} V_i(t) = v_s(t) \\ I_i(t) = \frac{1}{Z_0} \cdot v_s(t) \\ V_o(t) = 2V_i(t - \tau) - I_o Z_0 \\ I_o(t) = \frac{2V_i(t - \tau)}{Z_0 + Z_l} \end{cases} \quad (1)$$

Where  $V_i$  and  $I_i$  stand for the input voltage and current, respectively,  $V_o$  and  $I_o$  are the output voltage and current, respectively,  $\tau$  is the propagation time along the transmission line and  $Z_0$  is the characteristic impedance of the transmission line. If no reflections are assumed (perfectly matched mode of operation), (1) is valid for any time. The equivalent scheme for this case is shown in Fig. 2.

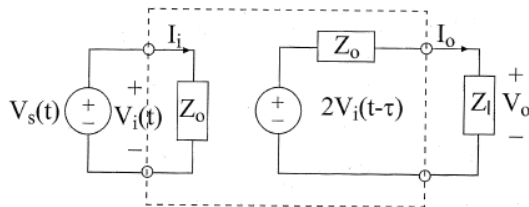


Fig. 2. Equivalent scheme in matched mode

The transmission line based energy compression network (TECN) consists of  $m$  transmission line segments, each of them assumed to be uniform and loss free (in principle). They differ from each other only by their delay time. The characteristics of those transmission lines are given in (2). Where  $L$  and  $C$  are the inductance and the capacitance per unit of

length, respectively,  $Z_0$  is the characteristic impedance and  $\tau_k$  the propagation time of a pulse along the  $k$ th transmission line segment.  $L$  denotes the length of the transmission line with the shortest delay time in the network.

$$\begin{cases} Z_0 = \sqrt{\frac{L}{C}} \\ \tau_k = k \cdot \tau \\ l_k = k \cdot l \end{cases} \quad (2)$$

Each of these transmission lines is terminated by a perfectly matched load,  $Z_{Lk} = Z_0$ , and each of them is energized by a periodical voltage pulse source  $v_{sk}(t)$ , with amplitude  $E$  and on time  $\Delta T = T/m$ , as depicted in Fig. 3. In practice, the group of different pulse source  $v_{sk}(t)$  is implemented by a single dc source,  $E$ , and a rotating switch that periodically connects the source to each of the transmission lines at the appropriate instants, see Fig. 3.

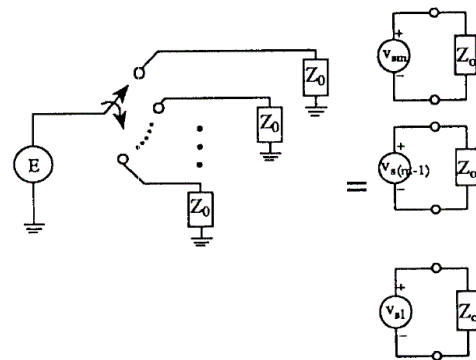


Fig. 3. Basic energy compression topology

The coupling networks are identical except for their delay time and the phase shift of the sources  $v_{sk}(t)$ , which feeds it. Let us define a delay operator  $D(\tau)$ , as

$$D(\tau)f(t) \equiv f(t - \tau). \quad (3)$$

Note that

$$D(\alpha \cdot \tau) = D^\alpha(\tau). \quad (4)$$

Referring to Fig. 3, each of the networks operates in matched mode and the  $k$ th network has a delay of  $k$  time  $\tau$

$$V_{ok}(t) = 2 \frac{Z_l}{Z_l + Z_0} \cdot D(k, \tau) V_{ik}(t) \quad (5)$$

$$V_{ok}(t) = 2 \frac{Z_l}{Z_l + Z_0} \cdot D^k(\tau) V_{ik}(t).$$

In the multiple source description the following relation can be assumed

$$v_{s1}(t) = v_{s2}(t - \tau) = \dots = v_{sm}(t - (m-1)\tau). \quad (6)$$

Using the definition of (3)

$$V_{ik} = D^{-1}(\tau) V_{i[k-1]} = \dots = D^{-(k-1)}(\tau) V_{i1} \quad (7)$$

Incorporating (5) and (7) and the matching condition yields the output voltage for any of the loads

$$V_{ok} = 2 \cdot \frac{Z_l}{Z_l + Z_0} \cdot D^k(\tau) D^{-(k-1)}(\tau) V_{i1} = D(\tau) V_{i1}. \quad (8)$$

From (8) it can be concluded that the voltage pulse appears on all loads simultaneously. Thus the dc source,  $E$ , sees a constant impedance load equal to the transmission lines characteristic impedance and supplies a dc power. The switch  $S$  rotates clockwise, starting at the input of the longest transmission line, thus, linking the voltage source  $E$ , to each of the transmission lines inputs for time duration of  $T/m$ ; here  $T$  denotes the period of the switch rotation. If  $v_{sk}(t)$  is the voltage pulse applied to the input of the  $k$ th transmission line, it can be defined as

$$\begin{cases} v_{sm}(t) = \begin{cases} E & 0 \leq t \leq \frac{T}{m} \\ 0 & \frac{T}{m} \leq t \leq T \end{cases} \\ v_{sk}(t) = D^{m-k} \left( \frac{T}{m} \right) v_{sm}(t) \end{cases} \quad (9)$$

The input current to the  $k$ th transmission line is found

$$I_{ik}(t) = \frac{1}{Z_0} D^{m-k} \left( \frac{T}{m} \right) v_{sm}(t) \quad (10)$$

The output currents are given by

$$\begin{bmatrix} I_{o1}(t) \\ I_{o2}(t) \\ \vdots \\ I_{om}(t) \end{bmatrix} = \begin{bmatrix} D^1(\tau) & 0 & \dots & 0 \\ 0 & D^2(\tau) & \dots & \vdots \\ \vdots & \vdots & \ddots & 0 \\ 0 & \vdots & \dots & D^m(\tau) \end{bmatrix} \begin{bmatrix} I_{i1}(t) \\ I_{i2}(t) \\ \vdots \\ I_{im}(t) \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} I_{i1}(t) \\ I_{i2}(t) \\ \vdots \\ I_{im}(t) \end{bmatrix} = \frac{1}{Z_0} \begin{bmatrix} D^{m-1}(T/m) \\ D^{m-2}(T/m) \\ \vdots \\ D^0(T/m) \end{bmatrix} \cdot v_{sm}(t). \quad (12)$$

If  $\tau$  is equal to  $T/m$ , then

$$\begin{aligned} I_{ok}(t) &= D^k(T/m) \cdot D^{m-k}(T/m) \cdot \frac{v_{sm}(t)}{Z_0} \\ &= D(T) \cdot \frac{v_{sm}(t)}{Z_0}. \end{aligned} \quad (13)$$

As can be observed, all output currents are identical and are a delayed replica of the input current to the  $m$ th transmission line. The first modeling step is performed according to the following assumptions:

- 1) Since the source in Fig. 3 supplies dc power (neglecting switching stray effects at the TECN input), the input part of the TECN can be modeled by the source,  $E$ , constantly connected to impedance  $Z_0$ .
- 2) Due to different delays of the transmission line segments the voltage waves reach the loads simultaneously as proven in (8).
- 3) Incorporation of lumped models of transmission lines (Fig. 1).

This leads to the model shown in Fig. 4, in which power is absorbed at the input at constant rate, and then distributed among  $m$  matched loads at the transmission lines outputs. It should be noted that output power appears in the form of simultaneous pulses at the loads.

To achieve energy compression, all the different loads of Fig. 3 must be integrated in a single load, yet the matched mode of operation must be preserved. Let us define the basic topology as the one resulting from the parallel connection of output terminals of the transmission lines. Noting that the output sources are identical (Fig. 4), the model of Fig. 5 is reached. To maintain matched conditions at the output the load impedance is now

$$Z_l = \frac{Z_0}{m} \quad (14)$$

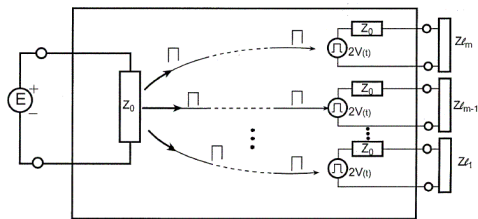


Fig. 4. Model of the pulse propagation, with distributed load

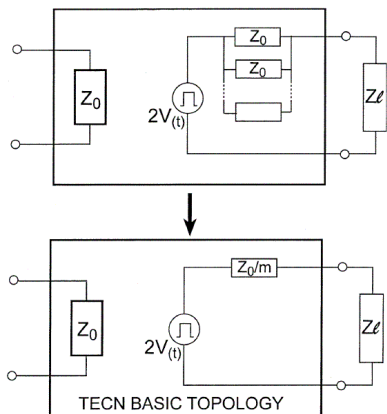


Fig. 5. Model of the basic TECN topology

The internal output voltage is identical to those of the model in Fig. 5

$$v_o(t) = \begin{cases} E & h.T \leq t \leq h.T + \frac{T}{m} \\ 0 & h.T + \frac{T}{m} \leq t \leq (h+1).T \end{cases} \quad (15)$$

**h** being an arbitrary integer. Thus, the load currents of Fig. 4 are summed up in the equivalent load of Fig. 5. In other words, current compression by a factor of **m** ((source power)/ (pulsed load power) =**m**) is achieved with respect to the input (during the output pulse duration).

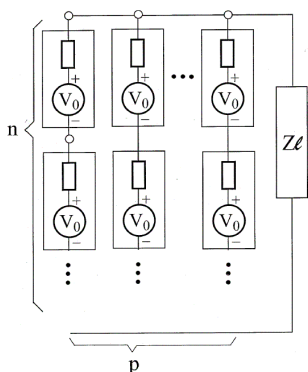


Fig. 6. Possible array connection at the output terminals

Generally the output terminals of the transmission lines shown in Fig. 4 may be connected in any symmetrical combination, if **m** can be decomposed

as:

$$m = n \times p \quad (16)$$

Then the output terminals can be connected in a rectangular array of **p** groups connected in parallel, each of them consisting **n** outputs connected in series, see Fig. 6. In this case the array is equivalent to a transformer connected to the basic topology [6], [7], having a transfer ratio of

$$a = n / p \quad (17)$$

In this case, matching imply

$$Z_l = \frac{n}{p} \cdot Z_0 \quad (18)$$

A simple example for possible choices of **n** and **p** that yields in voltage compression is described. In this mode

$$p = 1 \quad n = m \quad (19)$$

If all outputs are connected in series, matched operation conditions are achieved when load obeys (17)

$$Z_l = mZ_0 \quad (20)$$

In this case, the current-voltage parameters are:

$$I_l = \begin{cases} I_{source} \cdot (t - \tau) & T \leq t \leq (1 + (1/m))T \\ 0 & (1 + (1/m))T \leq t \leq 2T \end{cases}$$

$$V_l = \begin{cases} m \cdot E & T \leq t \leq (1 + (1/m))T \\ 0 & (1 + (1/m))T \leq t \leq 2T \end{cases} \quad (21)$$

It can be seen from the last expression that voltage compression is achieved in this case.

In principle, the delay of each transmission line segment in a TECN may be reduced by  $\tau$  without disturbing the TECN operation. In that case, the shortest segment is completely omitted. In practice, the transmission line length cannot be reduced beyond a minimum value. This value has to do with the degree of impedance matching at both input and output [8].

### 3 Simulation Results of The Transmission Line Based Pulse Generator

Simulations have been performed for various modes and compression ratios, all in good agreement with

the expected value. Ideal transmission lines were used for this part of simulations, with 50 Ω characteristic impedances and of 0.2, 0.4, 0.6 and 0.8 μs delay times. The input source is a 150 V dc voltage source.

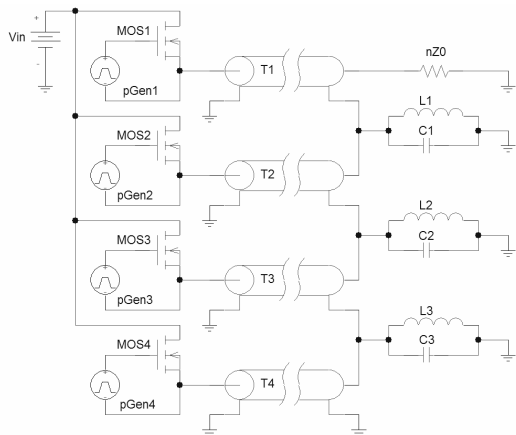


Fig. 7. Equivalent circuit model of a 4-stage wound transmission line topology

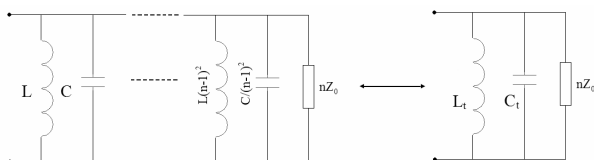


Fig. 8. Simplified versions of the equivalent circuit referred to the 1st stage.

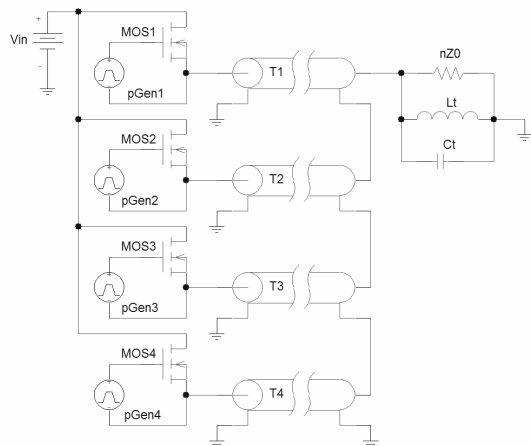


Fig. 9. Voltage compression mode: The topology used for simulation

Examination of the way in which the transmission lines are connected reveals that the outer conductors of each coaxial cable, at the output end of the lines, are connected to ground. To limit the consequent short-circuit currents, all the cables, except the bottom one, are wound on magnetic cores. The inductive effect of these windings together with their stray capacitance can be represented as in Fig. 7. The inductors are in the range of some mH and the capacitors are in range of some hundreds of pF. As

has been shown elsewhere [9] these inductors and capacitors can be reflected to the 1st stage of the stacked system with a factor  $n^2$ , which is determined by the stage  $n$  to which each component is connected, as shown in Fig. 8. By lumping these components together, the circuit shown in Fig.9 can be drawn.

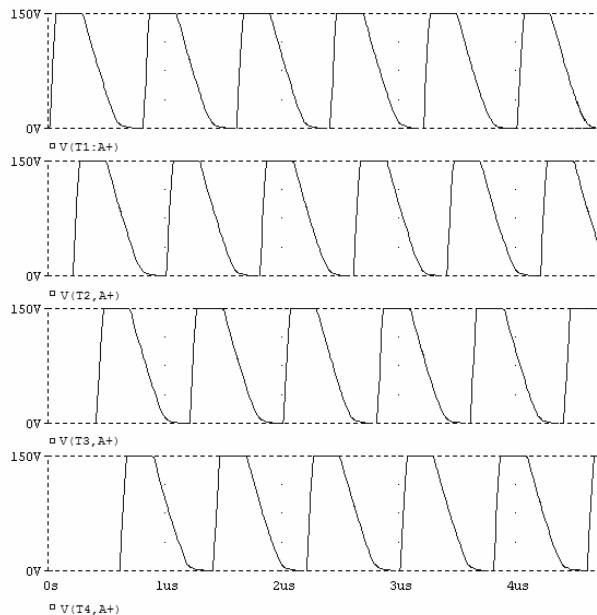


Fig. 10. Voltage compression mode: Voltage pulses applied to the transmission line inputs

Simulation results are shown in Fig. 10 and 11 for the voltage compression mode ( $n=4, p=1, Z_{load}=200 \Omega$ ). It's shown how equal amplitude time shifted voltage pulses are applied at the transmission lines inputs (Fig. 10) while in Fig. 11(a) it's shown that these pulses reach outputs simultaneously and build up 600V pulses across the load, as shown in Fig 11(b).

#### 4 Experimental Results of The Transmission Line Based Pulse Generator

Experiments were performed to validate the transmission line based energy compression method. 0.2 μs wide pulses were generated with an efficiency of 84%. The rotating switch shown in Fig. 3 was implemented by Power MOSFET's IRF640. Four coaxial transmission lines RG-58A/U of 50 Ω characteristic impedance and  $2/3c$  wave propagation velocity were used. The length difference from one line to the other results

$$\Delta l = d.v = d.(2/3).c = 0.2\mu s.2.10^8 = 40m.$$

The minimum length of the shortest transmission line was found experimentally:  $l_1=36$  m. Thus the rest of the lines were 76 m, 116 m and 156 m long. The source used was a transformer along with a proper rectifying circuit. A logic and drive circuit was built using an oscillator and a high-speed counter that along with opto-couplers and MOSFET drivers, provide the desired control signal for Power MOSFETs. Because of some restrictions in high voltage testing due to the measurement tools and probes limitations, experiments were performed with the source voltage of about 75 V that brings about 300 V load pulses. The results for the basic topology (voltage compression) are given in Fig. 12, which shows the voltage pulses generated across the load. The load impedance is 200  $\Omega$  in this case.

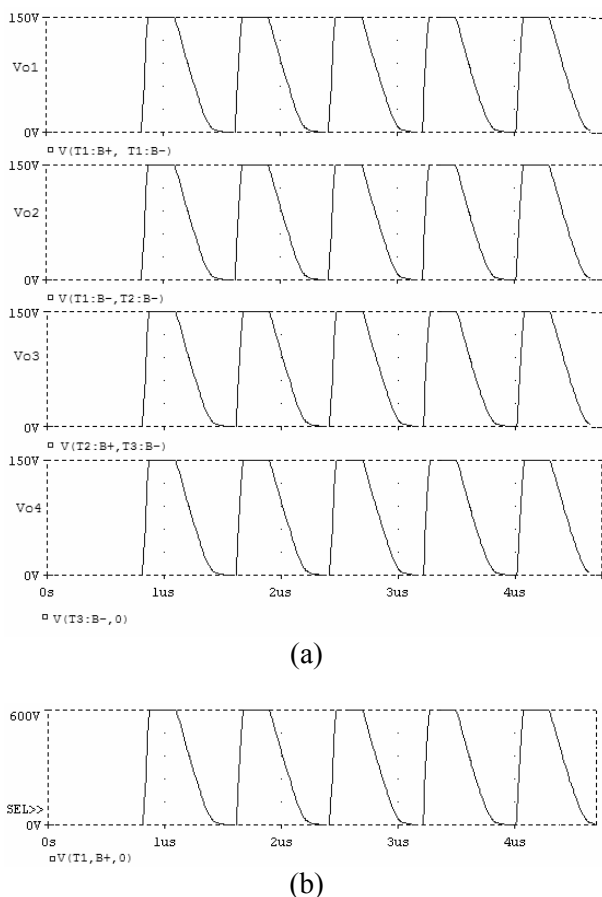


Fig. 11. Voltage compression mode: (a) Voltage pulses at the transmission lines outputs and (b) 600V pulses across the load

## 5 Conclusion

A method of energy compression was presented in this paper. The principle of operation was analyzed and verified by simulations as well as experiments, which all were in good agreement with expectations. SPICE models to describe temporal response of wound TECN were also presented which assume the cable shielding impedance as

a lumped impedance. A practical design example was performed, and experimental results are presented. With this setup, 300 V, 200 ns pulses were generated with an efficiency of 84%. About 11% losses are due to switching and conduction losses within the Power MOSFETs, capacitors ESR, and other stray effects associated with the rotating switch implementation and only 5% losses are generated by the actual TECN, which clearly validates the proposed method. In the experimental setup whose main purpose was to demonstrate the feasibility of concept, the efficiency is quite modest. For practical purposes, higher efficiency would be needed. It is expected that this method will be useful in high frequency, high voltage applications such as supplies for microwave tubes.

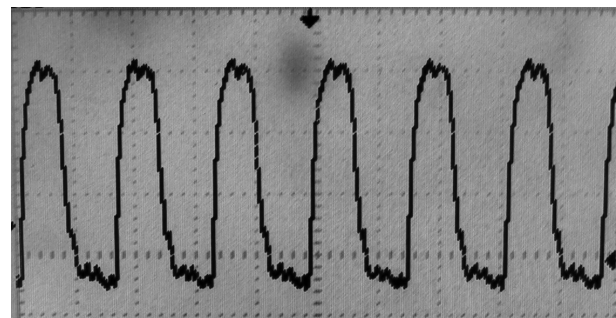


Fig. 12. Voltage compression mode: Load voltage 100 V/div, 500nS/div

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