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Fast Pumping Current in Two-Conductor Lines and its Application for Forming Powerful Rectangular Pulses

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Inductive energy storage devices are widely used in power pulse generators. At the same time, along with lumped inductive energy storage devices distributed inductive storage devices are used, made in the form of two-wire forming lines (FL) where the energy is stored in the form of a quasistatic magnetic field and is output in the form of a TEM-waves (Transverse Electromagnetic Modes) packets using keys of the opening type: ElectroExplosive Breakers (EEB), Plasma Opening Switches (POS), in various modifications, for example [1].
With the advent of solid state opening switches [2], pulse generators with lumped inductive energy storage devices began to be used much more often. However pulse generators based on two-wire forming lines and the solid state opening switches have not yet been properly used, which is probably due to the peculiarities of the operation of these breakers - the conditions for their opening and the short duration of their conductivity phase.
In this paper, we describe a method for rapidly pumping two-wire lines with current and using it to create generators based on two-wire lines and solid state opening switches.

Fast pumping current of forming lines

Traditionally, it is proposed to pump two-wire lines by current by connecting a voltage source to one of the ends of the line in the open state with the closed state of its other end (Fig. 1), for example [1]. If a constant voltage source *(E(t)=E=Const)* is used to pump the line, then the dynamics of the current and voltage at any point in the line ($x \in [0, l]$), for any moment of time (t), is determined by the following relationships.

For $t \in \left[0, \frac{x}{V}\right]$:

$u(x,t) = 0,\ i(x,t) = 0.$

For $t \in \left(\frac{2kl+x}{V}, \frac{2(k+1)l-x}{V}\right]$, at $k = 0, \infty, 1$:

$u(x,t) = E,\ i(x,t) = (2k+1)E/\rho.$

For $t \in \left(\frac{2kl+x}{V}, \frac{2(k+1)l-x}{V}\right]$, at $k = 1, \infty, 1$:

$u(x,t) = 0,\ i(x,t) = 2kE/\rho.$

Where:

l - line length,

ρ - line impedance,

V - TEM-wave propagation speed in the line,

t - time.

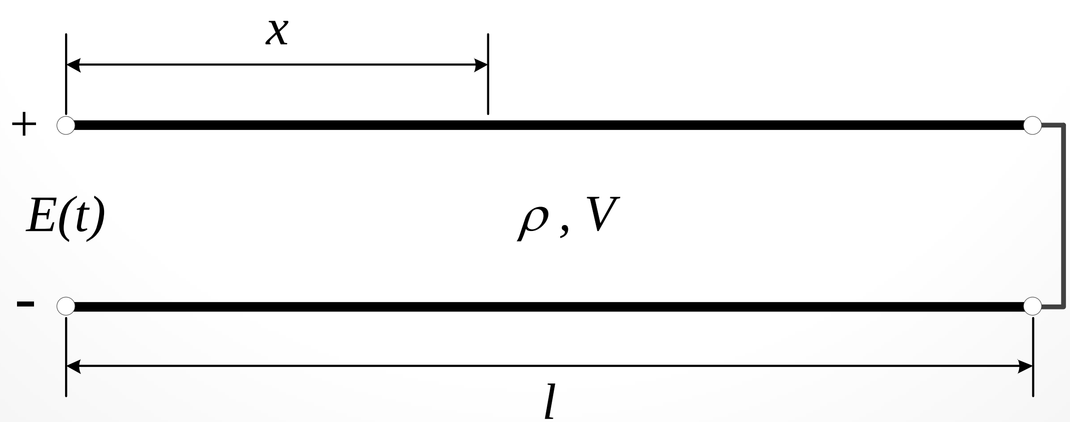

Fig. 1. Pumping the two-wire line from a constant voltage source.

It can be seen from the above relations that the current at any point in the line increases stepwise by value $\Delta i = 2E/\rho$ at time intervals $\Delta t = 2l/V$ and the same current value and zero voltage value at all points of the line occur only at time instants $t = 2kl/V,\ k = 0, \infty, 1$, at other times, the current and voltage at different points of the line can differ by $2E/\rho$ and E, respectively. Therefore a short pump time (a small number k) leads to a significant difference in the magnitude and structure of the energy stored in the line, which limits the length of the lines requiring fast current pumping in the absence of a significant charge (voltage).

This limitation can be circumvented by using composite two-wire lines made in the form of a chain of TEM-tees, each of which has two identical longitudinal arms and one transverse arm. In this case, the longitudinal arms of the tee have a length significantly greater than the length of the transverse arm. The transverse arms of the tees used to input energy into the line have a minimum length sufficient to form the TEM-structure of electromagnetic fields in them. The outer arms of the tees located at the edges of the composite line are short-circuited. The circuit of composite line is shown in Fig. 2, where: l - length of the longitudinal arm of the tee, $l^t \ll l$ - length of the transverse arm of the tee, ρ - impedance of the longitudinal arm, $\rho^t = 2\rho$ – impedance of the transverse arm.

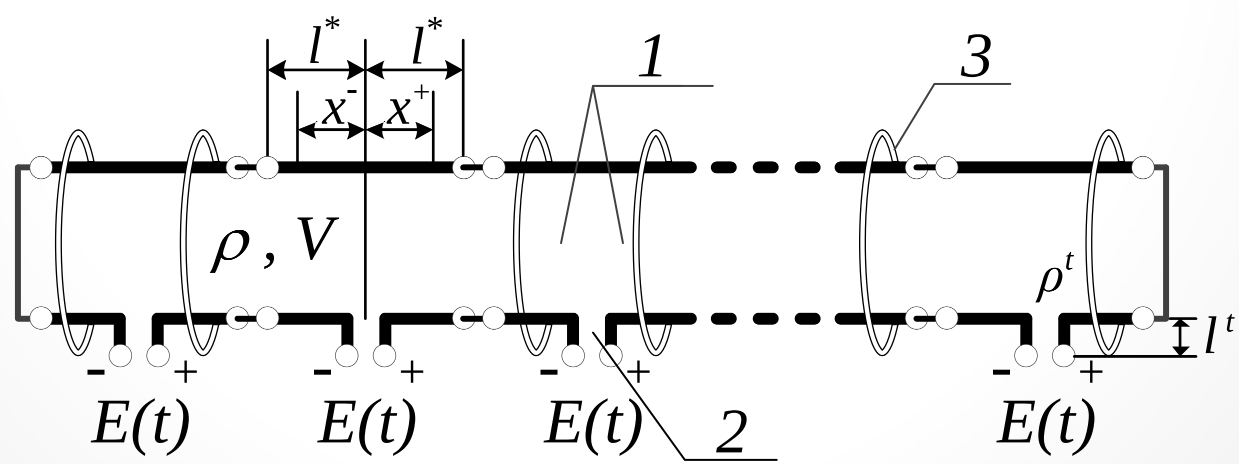

Fig. 2. Composite line. 1 – longitudinal arms of the tee; 2 – transverse arm of the tee; 3 – isolating inductance magnetic core.

When using sections with transverse arms of a negligible length and sources of constant voltage *(E(t)=E=Const)* with simultaneous switching-on, the dynamics of the current *i(x, t)* and voltage *u(x, t)* at the points of the longitudinal arms of the tees located at a distance $x^+ = x^- = x \in [0, l^*]$ from the transverse arm, can be defined by the following relationships.

For $t \in \left[0, \frac{x}{V}\right]$:

$u(x^+, t) = u(x^-, t) = 0, \;\; i(x^+, t) = \; i(x^-, t) = 0.$

For $t \in \left(\frac{kl^*+x}{V}, \frac{(k+1)l^*-x}{V}\right]$, at $k = 0, \infty, 1$:

$u(x^+, t) = -u(x^-, t) = E/2,$

$i(x^+, t) = \; i(x^-, t) = (k + 1/2)E/\rho.$

For $t \in \left(\frac{(k+1)l^*-x}{V}, \frac{(k+1)l^*+x}{V}\right]$, at $k = 0, \infty, 1$:

$u(x^+, t) = u(x^-, t) = 0, i(x^+, t) = \; i(x^-, t) = (k + 1)E/\rho.$

Where:

V – TEM-wave propagation velocity in the longitudinal arms of the tees,

x^+ - point of the right longitudinal arm of the tee at a distance *x* from the transverse arm,

x^- - point of the left longitudinal arm of the tee at a distance *x* from the transverse arm.

The same current value and zero voltage value at all points of the line takes place at time instants $t = kl^*/V, \; k = 0, \infty, 1$, at other time instants the current and voltage at different points of the line can differ by the quantities *E/2ρ* and *E*, respectively.

The transition from pumping a long forming line to pumping short sections allows to increase the slew rate of the current in the line and increase the uniformity of its energy state (increase energy storage in the form of a magnetic field compared with accumulation in the form of an electric field). An increase in the speed of pumping the line with current makes it possible to reduce the voltage of power supplies (*E*) and use semiconductor switches to commutate them.

Pulse generation by fast current pumped lines

The high speed of current pumping composite lines enables a creation of rectangular pulse generators based on forming lines and solid state opening switches, which are located at the end of the line where the load is. Unlocking the diode switch (pumping the diode switch in the forward direction) is carried out by a device that is autonomous from the state of the line, which begins to work until the moment the line is pumped with current. The line current pumping begins at the final phase of the forward pumping of the diode switch. In this case, the line pump current and the forward pump current of the diode have opposite directions, i.e. locking of the diode switch is carried out by the difference current with the dominance of the line current.

A generator circuit based on a composite forming line and a diode switch is shown in Fig. 3.

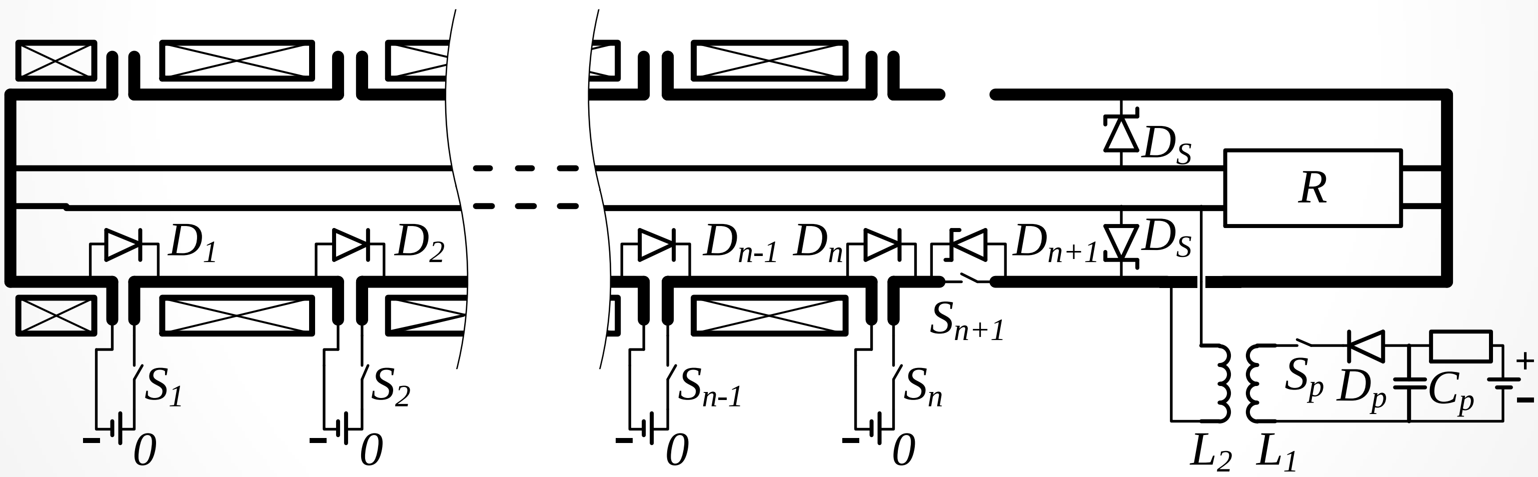

Fig. 3. Pulse generator. S_1-S_n - transistor switches of reverse current pumping; S_{n+1} – decoupling switch; D_1-D_n – diodes supporting reverse pumping current after opening the switches S_1-S_n; D_{n+1} – diodes to protect the decoupling switch S_{n+1}; D_s – diode opening switch; R – load; L_1-L_2 – a step-down transformer; S_p – forward pumping circuit switch; C_p – storage capacitor of forward pumping circuit.

The capabilities of this generator circuit are illustrated by the implementation of a pulse generator, where the diode switch operates in a mode close to the described in [3], characterized by the following parameters: forward pump time of the diode switch - 1400 ns, density of the forward pumping current diode switch – 20 A/$см^2$, reverse pump time of the diode switch - 200 ns, density of diode switch reverse pumping current - 120 A/$см^2$, current interruption time - 6-10 ns.

The generator is made of a 25-section forming line with a wave impedance of 50 Ohms, with a section length of 600 mm and a diode SOS-switch in the form of a series-parallel assembly with a total area of diode plates of 16 cm^2. Switching of the voltage sources to the transverse arms of the tees is carried out by parallel assemblies of 20 IXFB70N100X MOSFET-transistors with current rise time of 20 ns. Holding the current in the line after turning off the voltage sources is ensured by parallel assemblies of 7 DSEP2x25-12C diodes with a total dynamic resistance of less than 2 mOhm.

Since the forming line is connected in parallel with the diode switch, to prevent the leakage current through the line during forward pumping, a decoupling switch is used in the form of an assembly of 20 transistors, similar to the assembly of transistors in the transverse arms of the tees, which is switched on synchronously with the transistor switches of the sections. The decoupling transistors are protected by a parallel assembly of 7 avalanche diodes VS-90APS08L-M3.

The diode switch is pumped by forward current through a step-down transformer 1:60 with a coupling coefficient of 0.96. Forward pumping of the diode switch is initiated by closing the key SP. The rise time of the current in the forward pumping circuit is ≈610 ns, the current at a maximum is 350 A, and the current density at a maximum is 22 A/cm^2. The primary circuit of the transformer is an oscillatory circuit switched by an assembly of 40 IGBT-transistors VS-GT300YH120N. Primary circuit inductance 220 nH, primary circuit capacitance 8 μF, charging voltage 1050 V.

Pumping of line by the reverse current of the diode switch begins with the closure of a decoupling switch S_{n+1} and switches S_1-S_n in the transverse arms of the tees, witch connecting 980 V voltage sources to the input of the transverse arms of the tees. The moment starts pumping of line by reverse current may not coincide with the end of the forward current, it is only necessary that by the time the current through the diode switch is cut off, the current in the primary circuit of the forward pump circuit is zero, otherwise the shape of the voltage pulse at the load will be distorted. The pump time of the reverse current of the diode switch to a value of 2000 A is ≈210 ns. In the period between the opening of the S_1-S_n switches (the S_{n+1} switch opens after the formation of a voltage pulse at the load) and the moment of current interruption through the diode switch, the current in the line remains constant, that ease generator tuning and increases the stability of the input voltage pulse.

When the diode switch is opened, a rectangular pulse with a voltage of ≈50 kV is formed at a 50-ohm generator load.

Since the transistor switches of the sections work synchronously a common magnetic core can be used to decouple the sources of the sections, as was done in [4].

The dynamics of the currents through the diode and the voltage at the load are shown in Fig. 4, 5.

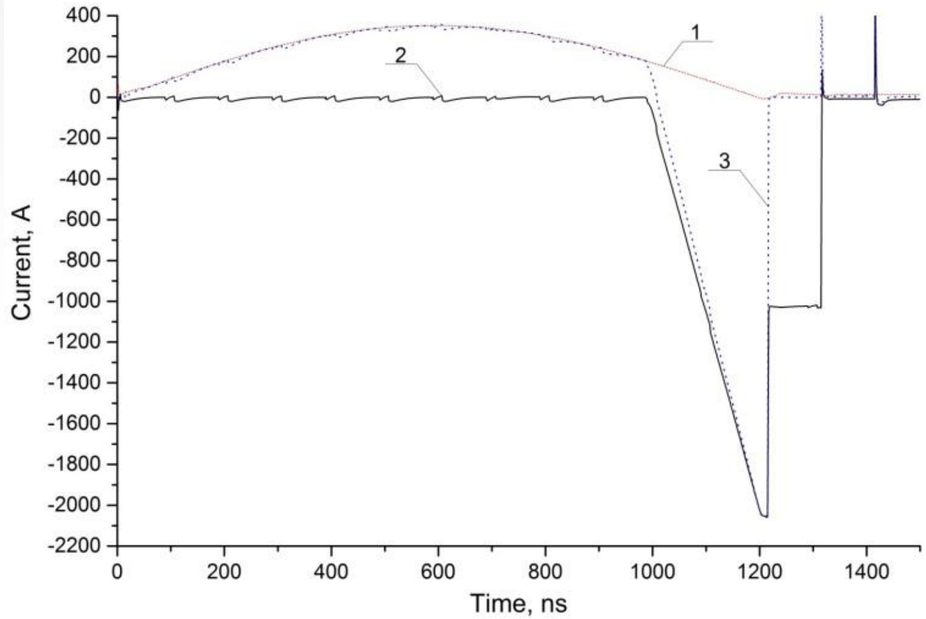

Fig. 4. Dynamics of currents through a diode switch. 1 - forward current; 2 – reverse current; 3 – resulting current through a diode.

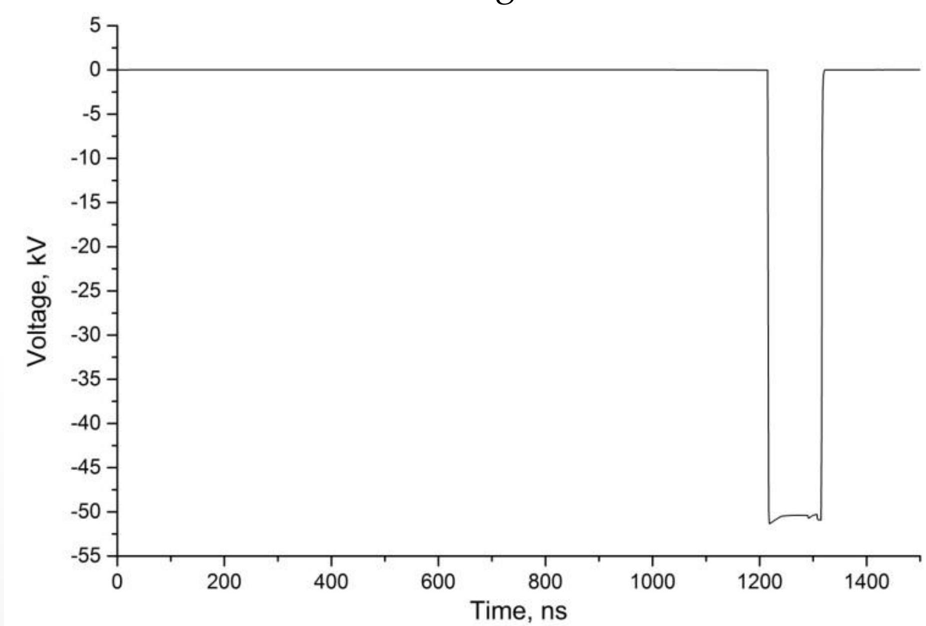

Fig. 5. Voltage on the load.

Conclusion

- The use of partitioned forming lines allows the lines to be pumped at a speed of $EV/\rho l^{*}[A/c]$, while the voltage at the points of the line does not exceed $\pm E/2[\mathrm{B}]$.
- Fast pumping allows various schemes of powerful rectangular pulse generators based on FL and diode switches. The independence of the currents of the forward and reverse pumping of the diode switch allows you to vary their ratio and thus the moment and speed of the current cutoff through the diode.
- The fast current pumping of lines makes it possible to reduce ohmic losses during the pumping process and reduce the voltage requirements of the power sources used to pump lines.

References

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