A PSPICE SIMULATION OF A PLASMA-FOCUS DEVICE DRIVEN BY A MAGNETIC PULSE COMPRESSION CIRCUIT

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Introduction

The plasma-focus device (PFD) discharge chamber consists essentially of two coaxial electrodes and an insulator across which the initial breakdown occurs. The central electrode attaches to a central header that provides an electrical connection to the PFD driver (pulser). Development of the plasma current leading to formation of a dense plasma region at the central electrode terminus can be conveniently subdivided into three main phases. First is the initial gas breakdown and the formation of the parabolic current front. Second is the hydromagnetic acceleration of a uniform axisymmetric current sheath toward the open end of the central electrode. The third part of the discharge is the rapid collapse of the current sheath toward the axis to form the dense plasma focus (this is the pinch phase).

Having in mind industrial applications (such as the X-ray microlithography), our main goal for the near future is to obtain very high average electromagnetic power delivered to the plasma-focus load, from the PFD driver (or pulser). The classical solution for the pulser (condenser discharged through a spark gap switch into the load) cannot be applied, because of the difficulties arising in the development of a spark gap switch capable of discharging pulse currents of 100 kA or higher at more than about 10 Hz repetition rate. The only method to reach the desired average output power is the magnetic pulse compression (MPC). The method is used in a large number of applications, which includes high-power lasers [1], particle accelerators [2], intense X-ray sources [3]. As it is shown in [2], the MPC method is extendible up to average output power levels of hundreds kW and even MW.

A 200 J/pulse, 50/100 Hz magnetic pulse compression circuit (MPCC) has been designed [4]. The circuit (fig. 1) has a 25 kV working voltage, and compresses a 29.5 μs / 1 kA pulse into a 560 ns / 100 kA plasma current pulse.

The transient analysis of the pre-breakdown phase

The analysis starts with the C3 capacitor charging from the previous one in MPCC (fig. 1). The C3 voltage is given by:

$$v_3(t) = \frac{V_0}{2}\left(1 - \cos\frac{\pi}{\tau_2}t\right), \tag{1}$$

where $V_0 = 25$ kV, $\tau_2 = 1.5$ μs.

In the pre-breakdown phase, the plasma current is zero. For this reason, one must connect a "bypass impedance" (R or L in fig. 1) in parallel with the load, in order to conduct the magnetization current of the last saturated inductor (L3). This current produces a pre-pulse voltage, before the high-voltage ($\cong$ 25 kV) appears on the load.

Before the τ_2 moment, L3 is unsaturated, its value being around 30 μH. At the τ_2 moment, L3 saturates (the "magnetic switch" goes in the "close" state), its value becoming suddenly 30 nH.

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The PSPICE circuit is shown in fig. 2. This circuit has three voltage-controlled switches. In the pre-breakdown phase, S3 is hold in the open state. During the 1.5 μs C3 charging time, S1 switch is in the closed state. S1 opens just at the v_3 maximum, such that the C3 capacitor cannot discharge back. In this way, S1 simulates the behavior of the L2 magnetic switch, through which C3 is charged from the previous capacitor (C2) in MPCC (fig. 1).

To simulate the change in L3 the S2 voltage-controlled switch is used. By closing this switch at 1.55 μs the C3 capacitor is discharged practically through Lsat in series with R or L bypass impedance.

The PSPICE pre-breakdown transient analysis was made up to 1.8 μs, for R = 1, 2, 3, 5, 10 Ω, and L = 1, 2, 3, 5, 10 μH. For the R values, the pre-pulse voltages are from 660 up to 5800 V. After L_1 saturates, the high-voltage rise-times are from 100 ns (for R = 1 Ω), down to 20 ns (if R = 10 Ω). Unfortunately, the shortest rise-time means the highest pre-pulse voltage.

For an L bypass impedance, the pre-pulse voltages are from 800 V to 6200 V. But the great advantage of the L impedance is the very short high-voltage rise-time: 1.5 - 2 ns for all the inductance values. A short high-voltage rise-time is a good condition for an optimum plasma-focus discharge.

The transient analysis during the discharge time

In the PSPICE circuit, the breakdown is simulated by closing the S3 switch at 1.6 μs.

It will be considered that after breakdown, during the acceleration phase, the plasma load is an inductance, linearly increasing in time, from 10 up to 20 nH (fig. 3a). Then, during the fast radial collapse (the pinch phase), the inductance rises rapidly (30 nH / 50 ns). In the last, post-pinch phase, the inductance rises slowly (10 nH / 350 ns). The plasma resistance is supposed to have a triangular time variation (fig. 3a), with a maximum value of 20 mΩ, at the end of the pinch phase.

The described load type complicates the integral-differential equations we have to solve in a numerical simulation of the plasma focus device. Nevertheless, by using PSPICE in a proper manner, the program is much simpler than a classical computer program for solving systems of integral-differential equations.

The PSPICE does not accept time-varying impedances [5]. These impedances can be however simulated by converting them into voltages or currents, which are further processed and finally are properly introduced into the main circuit. For example, for a time-varying inductance L(t), the voltage across it is:

$$V_L(t) = L(t)\frac{di}{dt} + i(t)\frac{dL}{dt}\,. \tag{2}$$

In the PSPICE program, a voltage source, varying in the same manner as L(t) is created. This source provides on an 1 Ω resistor a voltage which is numerically equal with L(t). For getting the derivative of L(t), a current source, numerically equal with L(t), has an 1 H inductance at its output. The output voltage will be numerically equal with dL/dt. Similarly, voltages which are numerically equal with i(t) and di/dt are created. Two other voltage-controlled voltage sources provide into 1 Ω output resistors two output voltages, equal with {L(t) di/dt}, and with {i(t) dL/dt}. Finally, in the main PSPICE circuit (fig. 2), the inductance is replaced with the EL voltage-controlled voltage source. This source makes an addition of the two above voltages.

The time varying plasma resistance is represented by the ER source (fig. 2).

In fig. 3, a typical set of results is shown. Curves b) and c) show the plasma current and voltage. Curve d) is the time-varying magnetic energy ($L\, I^2_{plasma}/2$).

Plasma sheath mechanical energy (fig. 3e) is the sum of translational and thermal energy, and is given by:

$$E_{mech} = \frac{1}{2}\int_0^t \frac{dL}{dt}\, i(t)\, dt\,. \tag{3}$$

For integration, the voltage i(t) dL/dt (the second term in (2)), is converted into a current source, charging a 2 F capacitor. The capacitor voltage is numerically equal with $E_{mech}(t)$.

The pinch voltage (i dL/dt) is shown in fig. 3f.

The obtained numerical data are in reasonable agreement with the typical ones in plasma focus experiments.

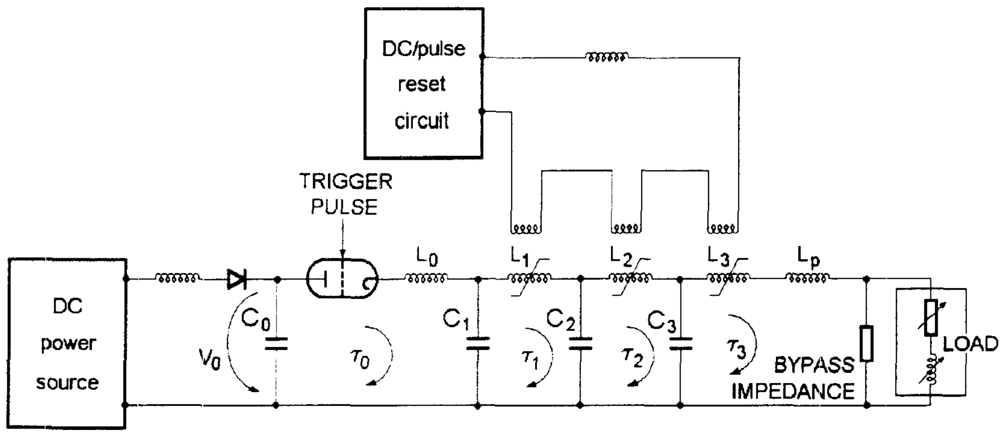

Fig. 1
The magnetic pulse compression circuit - MPCC (200 J / pulse, 50 / 100 Hz),
proposed for the plasma-focus soft-X-ray source.
$V_0 = 25$ kV; $C_0 = C_1 = C_2 = C_3 = 750$ nF / 30 kV;
$L_0 = 234.7\ \mu H$; $L_{1\ saturated} = 11.8\ \mu H$; $L_{2\ saturated} = 595\ \mu H$;
$L_{3\ unsaturated} \approx 30\ \mu H$; $L_{3\ saturated} = 30$ nH; $L_{load\ after\ discharge} + L_{parasitic} \approx 12$ nH;
$\tau_0 = 29.5\ \mu s$; $\tau_1 = 6.6\ \mu s$; $\tau_2 = 1.5\ \mu s$; $\tau_3 = 560$ ns (for a short-circuit load).

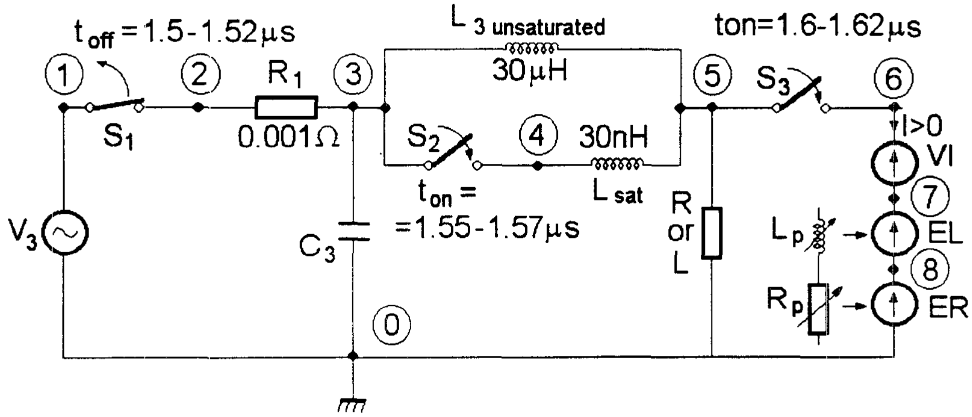

Fig. 2
The PSPICE equivalent circuit for the MPCC last stage,
having the plasma focus device as a load

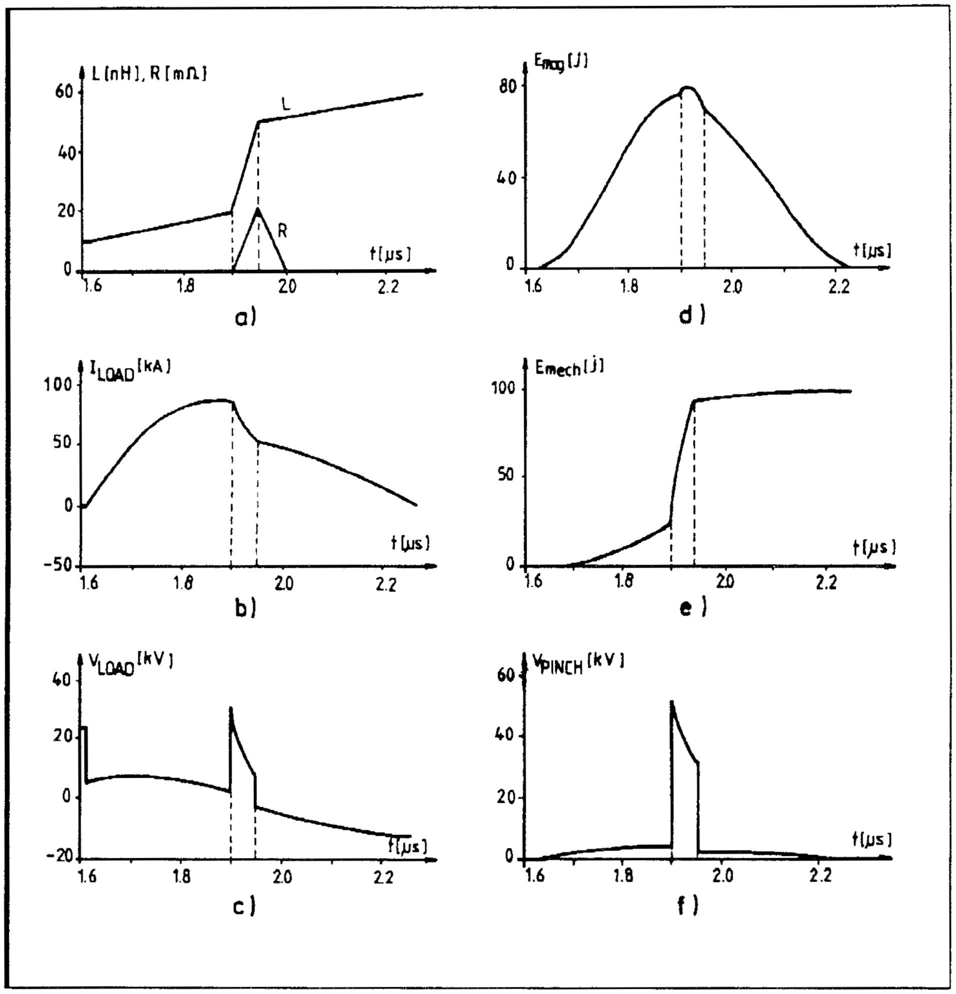

Fig. 3. a) **The supposed L(t) and R(t) components of the plasma impedance.**
b), c), d), e), f) : **The computed results for the PFD main parameters:** b) plasma current; c) plasma voltage; d) plasma magnetic energy; e) plasma sheath mechanical energy; f) pinch voltage.

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