Investigation of MPOS-LCM Cascade Circuits on the GIT-12 Generator

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Abstract – The paper analyzes two versions of a cascade circuit consisting of a microsecond plasma opening switch (MPOS) and a load current multiplier (LCM). In the first version, the MPOS is a load for the LCM; in the second version, the LCM is placed downstream of the MPOS. The both versions of the cascade circuit were tested in experiments on the GIT-12 generator with current switching into an equivalent load (a foil or a heavy planar wire array). At the instant of the MPOS, the voltage arising across the switch doubles the current amplitude in the plasma opening switch. The minimum inductance of this transition ensures the generation of a current pulse with a steep rise in the initially low-inductance load. In the circuit of the discharge of the inductive store, the amplitude switched into the load.

1. Introduction

A new pulsed power technology for the production of megawatt range is tested on the GIT-12 generator. The technology is based on a cascade circuit consisting of a microsecond plasma opening switch (MPOS) and a load current multiplier (LCM) [1]. Two versions of the cascade circuit are shown in Fig. 1. In the circuit A, the LCM at the output of the microsecond primary store increases the current amplitude (and rise time) in the MPOS which is a load for the LCM. On opening of the MPOS, the voltage arising across the switch ensures the generation of a current pulse with a steep rise in the initially low-inductance load. In the circuit B, the MPOS peaks the power of the microsecond primary store, and the LCM connected downstream of the plasma opening switch doubles the current amplitude switched into the load.

Let us compare the potentialities of the both versions for use on the GIT-12 generator. At the instant the current is switched into the load, the equivalent circuit of the cascade can be considered as a canonical circuit of the discharge of the inductive store \( L_1 \) with a current \( I \) into the inductance \( L_2 \) by the plasma opening switch with a steep rise of resistance from 0 to \( R_s \). Here \( L_1 \) is the inductance of the GIT-12 generator upstream of the MPOS; \( L_2 \) is the inductance of the load circuit. With no LCM, the load is remote from the MPOS to protect it against the plasma carried from the switch. The minimum inductance of this transition region depends on experimental conditions; for the GIT-12 generator, \( L_2 \sim 0.25L_1 \) [1]. Thus on the GIT-12 generator at \( L_2 = 0.25L_1 \) and \( R_s \equiv 0.5 \Omega \) [5], the current amplitude is \( I_0 = 0.8I \) with five-to-sevenfold pulse sharpening.

The LCM produces an additional inductance \( \Delta L \) in the discharge circuit. The additional inductance is the LCM inductance \( L_0 \), the load inductance \( L_d \), and the decoupling inductance \( L \). According to [2],

\[
\Delta L = L_0 + \frac{4I_m L}{L_d + L};
\]

\[
I_{sd} = \frac{2I_m L}{L_d + L},
\]

where \( I_m \) is the current at the LCM input; \( I_{sd} \) is the current in the LCM load circuit. Our experiments on the GIT-12 generator with load current multipliers [1, 5] suggest that conditions under which \( L \gg L_d, \Delta L \leq 0.5L_1 \) are feasible. For further analysis, let the maximum additional inductance be \( \Delta L = 0.5L_1 \) (the lower estimate for the current).

In the circuit A, the LCM increases the inductance of the primary circuit to \( L_{1d} = (L_1 + \Delta L) = 1.5L_1 \). The current amplitude in the plasma opening switch increases to \( I_A = 2I/I_{1/5} \equiv 1.6I \) due to its doubling in the LCM on retention of the conductivity stage duration. The current that can be switched into the load \( L_2 = L_2 \sim 0.1L_1 \) is up to \( I_A = 1.6I \) \( L_1/(L_1 + L_2) \approx 1.4I \sim 1.7I_0 \). Increasing the charge transport through the MPOS 1.6 times is bound to decrease \( R_s \) on opening of the switch [3]. If the charge through the MPOS is kept constant by reducing the conductivity stage, the amplitude of the load current is also 1.3 times higher than \( I_0 \) with no LCM.

In the circuit B, the storage inductance is equal to \( L_1 \), the load inductance is \( L_2 = \Delta L = 0.5L_1 \). With the LCM, which doubles the current amplitude in the low-inductance load \( L_z \), the load current can be expressed as \( I_B = 2I/L_1/(L_1 + \Delta L) \equiv 1.33I \approx 1.65I_0 \).

With a microsecond current pulse in the switch and its resistance in the open state \( R_s \sim 0.5 \Omega \), the current rise time in all modes is \( T_r \approx 2.2L_m/R_s \leq 150 \text{ ns} \), where \( L_m = L_{1d}/L_2(L_1/2 + L_2) \).

Thus, combining the two tested pulsed power elements allows a several-fold decrease in the current rise time in the load and a near-double increase in the energy transferred to the load: \( (I_B/I_0)^2 \approx 2.9 \) (1.7), \( (I_B/I_0)^2 \approx 2.6 \), where \( I_0 \) is the amplitude of the load current with power amplification without the LCM.

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2. Tests of the cascade circuit A

The circuit A was tested on the GIT-12 generator. Schematic of the cascade circuit is shown in Fig. 2. The LCM with a vacuum-insulated ferromagnetic core (the current multiplication factor is 2 [1]) is built in the internal cathode cavity of the GIT-12 central unit. The LCM design is described in [1].

A foil load of diameter 100 or 20 mm was placed at the center of a radial line with a cone of $10^\circ$ (Fig. 3). The derivative of the generator current at the LCM input and upstream of the MPOS was measured by inductive grooves $I_{in}$, $M_1$, in the load by magnetic probes ($B$-dot) $M_2$, and $M_1$ placed on a radius of 7 and 12 cm, respectively. The currents were obtained by integrating the signals from the probes. The voltage $U_L$ across the collector of the GIT-12 central unit, i.e., the voltage at the LCM input was measured by an inductive divider. In the experiments, the charge voltage of the Marx generator was 50 kV.

Figure 3 shows waveforms for shot No. 1132 into the $\varnothing$100-mm foil load ($L_d \equiv 5$ nH) at $t_d = 8 \mu$s. The amplitude of the MPOS current is 5.6 MA with a rise time of 920 ns. No clearly defined current switching into the load is found. The $B$-dot probes placed on a radius of 12 and 7 cm ($I_d1$ and $I_d2$, respectively) show the current sheet moving with a velocity of $\sim 1.2 \cdot 10^8$ cm/s from the MPOS to the load. On a diameter of 140 mm, the current amplitude increases to 4.3 MA in 200 ns. A mode close to that of a plasmodynamic multishell plasma flow switch [6] is observed due to the propagation of the plasma into the region between the plasma guns and the load in a time $t_d$ and to the removal of part of the plasma from the MPOS by the current sheet.
In this geometry, we managed to eliminate the effect by decreasing $t_d$ to $\leq 6 \mu s$ and by placing a shield near the plasma guns from the side of the load (Fig. 2, at the left). This led to a decrease in MPOS current amplitude to $\leq 5$ MA, but made it possible to switch the current into the load of increased impedance with moderate loss in the energy transferred to the load ($B$-dot signals in the radial line are recorded nearly at a time). Figure 4 shows waveforms for shot No. 1139 into the $\varnothing 20$-mm foil load ($L_d \approx 14$ nH) at $t_d = 6 \mu s$. At an MPOS current amplitude of 4.35 MA with a rise time of 730 ns, a 3.5-MA current was switched into the 14-nH load in 110 ns. The MPOS voltage reached 700 kV at a switch resistance of $\approx 0.4 \Omega$.

In these modes, the problems arose with the electric strength at the LCM output: bridging of the convolute and breakdowns of the vacuum insulation took place. Moreover, this circuit imposes increased requirements on the volt-second characteristic of the ferromagnetic core because the core is affected not only by the voltage pulse produced across the MPOS and but also by the microsecond voltage at the stage of energy delivery into the circuit inductance due to the finite inductance between the LCM output and the MPOS. Calculations show that for an implosion time of 170 ns with a load inductance increment $\Delta L_d = 9$ nH, the voltage across the decoupling inductance is higher than 500 kV and the volt-second integral of the core is greater than 100 mV $\cdot$ s. In the experiment, the volt-second integral of the core made of 10 rings was $\approx 90$ mV $\cdot$ s. Therefore, Z-pinch experiments require an increase in the cross-section of the core and in the electric strength of its vacuum insulation.

3. Tests of the cascade circuit B

The cascade circuit B consists of series-connected MPOS, LCM, and load unit. The circuit is mounted inside a shell of diameter 880 mm. Attaining the maximum current amplitude requires minimizing the inductance of the entire circuit section along the power flow downstream of the plasma opening switch. For this purpose, the LCM was placed into the internal cavity of the central electrode of the coaxial MPOS. This made it possible to use efficiently the volume of the cascade case and to minimize its inductance. Fig. 5 shows schematic of the cascade design with the load unit arranged on the collector of the GIT-12 central unit.
The coaxial plasma opening switch has a transparent anode consisting of 32 rods placed on a diameter of 790 mm and a solid cathode of diameter 700 mm. A plasma crosspiece is preliminary produced using 96 cable plasma guns placed on a diameter of 880 mm and powered by six pulsed sources. The design and the operating mode of the plasma guns are the same as those in the circuit A. The plasma guns are arranged in two rows: 64 and 32 plasma guns in the lower and upper row, respectively. The plasma guns of each of six units are symmetrically connected along the azimuth to produce a homogeneous cylindrical plasma shell.

The load current multiplier is placed inside the MPOS cathode and is similar in design to the LCM in the circuit A. The multiplier is two segments of vacuum coaxial lines formed by two hollow toroids with a common axis and connected in series from the side of the generator and in parallel from the side of the load using a 12-channel post-hole convolute. In the vacuum cavity of the inner toroid (decoupling impedance), a ferromagnetic core with a volt-second integral of \( \sim 110 \text{ mV} \cdot \text{s} \) is located.

The load-in-to the load is a vacuum coaxial segment of diameters 370 mm/340 mm and height 140 mm with a radial coaxial-to-planar load transition. The inductance of the secondary circuit with the LCM \( L \) is \( \sim 35 \text{nH} \). This makes it possible to switch up to 75\% of the primary store current on opening of the MPOS and to obtain a load current \( I_L \) \( \sim 1.5 I_1 \) with an LCM multiplication factor \( K = 2 \).

The current was measured with magnetic loops \( M_1, M_L \) and inductive grooves \( I_w \) the signals from which are proportional to \( dI/dt \) (see Fig. 5). The currents were obtained by integrating the signals with regard to the sensitivity and transition characteristics of the probes. The voltage was measured with a short-circuited segment of a high-resistance vacuum line \( (UL) \), which is a support of the GIT-12 central collector. In the experiments, the charge voltage of the Marx generator was 50 kV.

Figure 6 shows waveforms for shot No. 1215 into a 3.5-nH static inductive load on operation of the plasma guns 7 \( \mu \text{s} \) earlier than the Marx generator is turned on. The MPOS current reaches 4.2 MA in 1.45 \( \mu \text{s} \). On opening of the MPOS, a voltage pulse of amplitude 750 kV is generated and the amplitude of the load current reaches 6 MA with a rise time of 300 ns and a rate of rise of 40 kA/ns. As the load inductance is increased to \( \sim 7 \text{nH} \), the current amplitude decreases to 5.3 MA. The obtained characteristics of the open MPOS are lower than those for the LCM-free operation of the switch into an inductive load equivalent to the LCM + \( Ld \) circuit. This effect is due to the processes occurring in the MPOS-to-LCM transition region and is analyzed in [7].

4. Conclusion

Two versions of the cascade circuit consisting of a plasma opening switch and a load current multiplier were analyzed. The both versions demonstrate the feasibility of decreasing the microsecond rise time of the generator current \( \sim 5 \) times with up to 1.5-fold increase in the amplitude of the load current.

In the circuit A, a 4.3-MA current with a rise time of 200 ns was switched into the load at a generator current of 2.8 MA/\( \mu \text{s} \). The problem in the version is to preclude the entry of the plasma into the load region. Elimination of this effect in the circuit decreases the amplitude of the load current to 3.5 MA/110 ns. This version is characterized by current leakage at the LCM output to the point of breakdowns in the region of the convolute and core.

In the circuit B, a current of amplitude \( \sim 6 \text{ MA} \) with a rise time of 300 ns was switched into the 3.5-nH inductive load at an amplitude of the GIT-12 generator current of 4.2 MA through the plasma opening switch with a rise time of 1.5 \( \mu \text{s} \). In the equivalent of a planar load with an initial inductance of 9 nH, a current of \( \sim 5.6 \text{ MA} \) with a rise time of 300 ns was obtained. The circuit B is found to be more preferable in terms of the set of attained load parameters and simplicity of realizing efficient operation of the cascade circuit. This circuit is basic for Z-pinch experiments.

References


