Adapting of a Plasma Opening Switch with a Load Current Multiplier in Experiments on the GIT-12 Generator

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Abstract – In the work, we studied the operating modes of a microsecond plasma opening switch (MPOS) on the GIT-12 generator on switching the current from the primary energy store into the load circuit for which a load current multiplier (LCM) with a ferromagnetic core was used. The MPOS-to-LCM transition region was optimized to obtain the maximum pulse power in the load. It is shown that the proposed design allows a fivefold increase in load current amplitude.

1. Introduction

The objective of the work was to increase the current amplitude and the pulse power at a Z-pinch load. For this purpose, a cascade circuit was proposed which consisted of a primary capacitive energy store, a microsecond plasma opening switch (MPOS), a load current multiplier (LCM), and a Z-pinch load [1, 2]. Schematic of the cascade circuit is shown in Fig. 1. At the conductivity stage (R_s ~ 0), the MPOS transfers the energy of the primary capacitive store to the magnetic field energy of the primary circuit with inductance L_s and current I_s. On opening of the switch (R_s >> (L_0)/(C_0)^2), the current from the primary circuit is switched into the secondary circuit of inductance L_2. For this canonical circuit of the inductive store, the limiting current amplitude in the secondary circuit is

\[ I_2 = I_1 \frac{L_1}{L_1 + L_2}. \]  

For the abruptly increasing MPOS resistance from 0 to R_s, the rise time of the current I_s is

\[ \tau_s = 2.3 \frac{L_s}{R_s}, \text{ where } L_s = \frac{L_1 L_2}{L_1 + L_2}. \]  

In the cascade circuit, the inductance L_2 is determined by the inductance of the MPOS-to-LCM transition region (L_m), the inductance contributed by the LCM to the discharge circuit (L_d), the load inductance (L_0), and the decoupling inductance (L). Using the law of conservation of magnetic flux for the secondary circuit, analysis made in [2], and expression (1), we can write

\[ L_2 = L_s + L_1 + \frac{4 L_d L}{L_d + L}; \]  

\[ I_d = \frac{2 I_s L}{L_d + L} = \frac{2 I_s L_1}{L_1 + L_1 + L + \frac{4 L_d L}{L_d + L}}, \]  

where \( I_d \) is the current of the load placed at the LCM output. Our experiments show that for the LCM with a ferromagnetic core, the conditions \( L >> L_d \) and \( L_s = (L_1 + L_2) \leq 0.25 L_1 \) are feasible [1]. In this case, expression (4) is simplified as follows:

\[ I_d = \frac{2 I_s L_1}{L_1 + L_1 + 4 L_d}. \]

Expression (5) suggests that the amplitude of the load current \( I_d \) depends strongly on \( I_d \). Let us demonstrate this with the following example. Let there be optimum conditions with a secondary circuit inductance \( L_2 = 0.25 L_1 \) and minimum load inductance \( 4L_{d_m} = 0.05L_1 \); the current \( I_1 \) and the resistance \( R_s \) be constant.

Figure 2 shows the time of the transient process and the amplitude of the load current at a fixed interval equal to the current rise time \( \tau_0 \) for \( L_{d_m} \) in relation to \( L_d/L_{d_m} \). The diagrams are normalized to the values corresponding to the transient process at \( L_{d_m} \):

\[ \tau_0 = 2.3 L_{d_m}/R_s, \text{ where } L_{d_m} = 2 I_s L_1 (1 - \exp(-\tau_0/\tau))(L_1 + 0.25 L_1) = 1.44 I_1. \]

The load inductance is increased five...
times (for the GIT-12 generator, from 1.5 to 7.5 nH),
the time of the transient process increases more than
1.5 times, and the amplitude of the load current with a
rise time \( \tau_0 \) decreases from 1.44\( I_1 \) to 1.07\( I_1 \). This
situation takes place with constant \( R_s \), which is not a
priori obvious. As shown in [3], variation in \( L_2 \) affects
\( R_s \). How this effect reveals itself in the cascade circuit
is just to be ascertained in the work.

![Fig. 2. Load parameters in relation to the load inductance
(the quantities are normalized to the characteristics of the
process for \( L_{dm} \))](image)

2. Experimental facility

The cascade circuit was designed using data of our
experiments on an MPOS with an amplitude up to
5 MA [3] and a microsecond megaampere current
multiplier in a low-inductance load [1,4]. The cascade
circuit uses vacuum insulation, and therefore the con-
ditions of magnetic self-insulation should be met in
the energy transport channel to the load, lest the vac-
uum gaps limit the power transport to the load. At the
same time, the gaps must be as small as possible to
decrease the secondary circuit inductance \( L_2 \) and to
attain the maximum current amplitude. Emphasis
should be placed on combining the electric strength of
vacuum coaxial magnetically self-insulated transmis-
sion lines (MITL) and the voltages produced on open-
ing of the MPOS. In papers on MITL’s [5–7], the oper-
ating electric field strength in vacuum lines varies
greatly depending on both voltage pulse durations and
experimental conditions. The velocity with which the
dense electrode plasma bridges the vacuum line gap is
\((2–3) \cdot 10^6 \text{ cm/s}\). With the expected time of the tran-
sient process \( \leq 500 \text{ ns} \) and with no special surface
conditioning of the MITL electrodes to improve the
insulation characteristics, a value of the operating
electric field strength of 1 MV/cm seems reasonable.
Our studies show that the voltage amplitude at the
MPOS output can reach 1.5 MV [3]. The above set of
parameters suggests that the MITL gap must be no
less than 1.5 cm.

The cascade with series-connected MPOS and
LCM is placed inside a shell with a diameter of
880 mm. Figure 3 shows the design of the cascade
(see [8]). The coaxial MPOS with electrode diameters
of 790/700 mm has 96 plasma guns. For the produc-
tion of a plasma shell of varying density profile

![Fig. 3. Design of the cascade for experiments on the GIT-12 generator: MPOS – microsecond plasma opening switch; LCM –
load current multiplier with a ferromagnetic core](image)
lengthwise the switch, the plasma guns are arranged in
two rows and can be triggered with controllable delays
relative to each other. The maximum number of the
plasma guns in the lower row is 64, and in the upper
row, it is 32. In the optimum modes, 64 plasma guns
operated 1.5–2 $\mu$s earlier than 32 plasma guns, and the
latter in turn operated 5 $\mu$s earlier than the Marx generator.

For minimizing the inductance $L_2$, the LCM was
placed in the internal cavity of the central electrode of the coaxial MPOS. This made it possible to efficiently
use the volume of the cascade case and to minimize its
inductance. The LCM is two vacuum coaxial seg-
ments 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 with a
12-channel post-hole convolute. The ferromagnetic
core is placed in the vacuum cavity of the inner toroid to
decrease the current loss and to double the ampli-
tude of the load current. The core consists of 11 rings
of outer diameter 620 mm. The rings of the ferromag-
netic core are wound from ET-3425 tape (of width
18 mm and thickness 50 $\mu$m); the total cross-section
of the rings is 520 cm$^2$ and is rated at a volt-second
integral of 130 mV $\cdot$ s. The core is placed in a stainless
steel case. The case with the ferromagnetic core rests
upon an inner central electrode of diameter 220 mm.
The other side of the LCM is fixed on the lower anode
flange of the load unit with 12 rods that serve simulta-
neously as central electrodes of the post-hole convo-
lute. The inner surface of the chamber walls and the
outer surface of the case are electrodes of the LCM vacuum coaxial segments. The anode of the load unit
is fixed on a shell of diameter 880 mm with 12 vanes.
The lead-in to the planar load from the LCM coaxial
output is a radial line with a transparent anode. The
inductance of the LCM–load section is 6.8 nH. The
initial inductance of the planar load is varied between
1.3 and 4 nH.

A peculiarity of this design is the MPOS-to-LCM
transition region that should meet several mandatory
requirements. First, the transition region must not
limit the MPOS characteristics on opening and must
have high electric strength in the submicrosecond
range of energy delivery into the load. Second, this
region must limit the plasma inflow to the region of
the LCM and load unit. Third, it must display suffi-
cient mechanical strength where the LCM with the
ferromagnetic core is suspended on a cantilever. These
requirements are met by using vane fixation of the
load anode unit and shielding electrodes. Figure 4
shows the cascade on the collector of the GIT-12 gen-
erator without the upper flange.

3. MPOS tests

In preliminary experiments, we selected the synchro-
nization mode of the plasma guns and Marx generator
and determined the characteristics of the coaxial
MPOS of the chosen interelectrode geometry with the
load inductance equal to the inductance of the secon-
dary circuit with the LCM. The MPOS geometry was
the same as that shown in Fig. 3, and without the
LCM the load was an MITL section of diameters
880/510 mm. All tests were performed in the first-shot
mode as is in experiments on Z-pinch loads.

Fig. 4. Photo of the cascade on the collector of the GIT-12
generator

Fig. 5. Characteristic waveforms of the generator current $I_1$, load current $I_2$, $U_L$ signals, and calculated MPOS current $I_s$, voltage $U_s$, and resistance $R_s$ for the operation without the LCM

In terms of the maximum current switched through
the MPOS and maximum voltage on its opening, the
optimum delays were $t_d = 6$–8 $\mu$s. Figure 5 shows
waveforms for a shot into the 40-nH load at $t_d = 8$ $\mu$s.
At the conductivity stage of the switch $t_c = 1.5 \mu s$, the current amplitude was 4.3 MA. On opening, the voltage amplitude across the MPOS reached 1.1 MV and a 3-MA current with a rise time of 250 ns was switched into the load. As the load inductance was doubled ($\Omega_{320}$ mm inner electrode of the MITL), the MPOS voltage was 1.2–1.4 MV and the amplitude of the current switched into the load was ~ 2 MA. The characteristics of the MPOS at the conductivity stage remained constant.

4. Cascade tests

The cascade shown in Fig. 3 was tested with the LCM free from the ferromagnetic core (the inductance of the vacuum cavity of the inner toroid $L_{\text{load}} \approx 60 \text{ nH}$) for a static inductive load $L_d = 3.5 \text{ nH}$. In this mode, the multiplication factor of the current transformer was 1.9.

Figure 6 shows waveforms for a shot on operation of the plasma guns $t_j = 7 \mu s$ earlier than the Marx generator was turned on. The MPOS current reached 4.2 MA in 1.45 $\mu s$. On opening of the switch, a voltage pulse of amplitude 750 kV was produced, and the amplitude of the current switched into the load was ~ 2 MA. The characteristics of the MPOS at the conductivity stage remained constant.

As the load inductance is increased, the current at the LCM input and the load current decrease, though the $I_L$ signal and $U_L$, as a rule, increase; however, the high-voltage stage becomes shorter. Figure 7 shows waveforms of the current for the operation into the load of inductance ~ 7 nH. The current lost in the transition region (the current $I_{\text{loss}}$) was measured with an ML probe. The difference between the currents $I_{\text{ML}}$ and $I_{\text{in}}$ can reach $\geq 500 \text{ kA}$, the switch resistances $R_s$ calculated from these currents differ ~ 2 times. On disassembling, traces of the electron beam on the anode flange in the transition region are found. Calculations show that with a constant amplitude of the generator current $I_1 = 4.2 \text{ MA}$, the three-fold increase in switch resistance (from 0.2 to 0.6 $\Omega$) increases the current amplitude in a 500-$\mu g/cm$ Z-pinch load from 3.2 to 4.3 MA with a decrease in implosion time from 310 to 230 ns.

The geometry of the MPOS-to-LCM transition region was optimized. The cathode and the anode were equipped with shielding electrodes, and the interelectrode gap in the transition region was increased (Fig. 3, region $I_{\text{loss}}$). Finally, in several iterations, the geometry was obtained that provided more efficient operation into a planar wire array of initial inductance 7–10 nH. In the optimized geometry, experiments were performed on the LCM with the ferromagnetic core and planar load. On implosion of a planar wire array, the passage of the current sheet falls mainly on the final implosion stage $\leq 20\% I_{\text{imp}}$. Therefore, the operation into the inductance equal to the initial load inductance makes it possible to estimate the current through the array and its kinetic energy.

Figure 8 shows waveforms and characteristics of the MPOS for shot No. 1295 into a planar wire array (Al, 100 $\mu m$) of initial inductance ~ 8.5 nH. For an MPOS current of 4.3 MA with a rise time of 1.5 $\mu s$, a current of ~ 5.2 MA with a rise time of 300 ns was switched into the load. The maximum MPOS voltage reached 930 kV, and the switch resistance was 0.4 $\Omega$.

![Image](image_url)

**Fig. 6.** Waveforms for a shot into the 3.5-nH load at $t_j = 7 \mu s$: $I_1$ – generator current; $I_{\text{in}}$ – current at the LCM input (current in the secondary circuit on opening of the MPOS); $I_d$ – load current

**Fig. 7.** Waveforms of the generator current $I_1$, current at the LCM input $I_{\text{in}}$, current from the ML probe $I_{\text{ML}}$, load current $I_d$, and voltage $U_L$

**Fig. 8.** Characteristic waveforms for a shot into the 8.5-nH load with the LCM and ferromagnetic core: $I_1$ – generator current; $I_d$ – load current; $U_L$ – voltage measured 25 nH upstream of the MPOS. The calculated MPOS current $I_s = (I_1 - I_{\text{in}})$, voltage $U_s(t)$; and resistance $R_s(t) = U_s(t)/I_s(t)$
5. Conclusion

The MPOS–LCM cascade circuit was optimized. The modified MPOS-to-LCM transition region and the choice of the operating mode of the plasma guns producing an initial plasma shell allowed a satisfactory match between the MPOS and the LCM. An MPOS voltage up to 1 MV was obtained. This result points to the applicability of this circuit in experiments on implosion of Z-pinch loads with currents of about 5 MA. The MPOS characteristics obtained on switching the current into the LCM are lower than those into the coaxial segment located farther along the power flow. This is due to the weaker magnetic field at the cathode on opening of the switch during the operation into the LCM (see [3]). Note also that earlier experiments on planar wire arrays of mass 500–1000 μg/cm demonstrated a strong effect of $dL/dt$ on the maximum amplitude of the load current. Minimization of $L_d$ is one of the basic requirements for efficient operation of the LCM into a Z-pinch load.

References

[1] V.A. Kokshenev, B.M. Kovalchuk, F.I. Fursov, and N.E. Kurmaev, “Cascade from power amplifier and current transformer for Z-pinch experi-
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