Investigation of the POS Characteristics in Several Schemes Delivering MA Current Pulses to Low Impedance Loads on GIT12

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Abstract – The efficiency of current switching to a low-impedance load has been analyzed using two circuits. The circuit B where a low-impedance load is connected upstream of a plasma opening switch (MPOS) has demonstrated a high current efficiency and revealed a considerable effect of the MPOS magnetic field on the closure rate and on the MPOS resistance during the high-voltage phase. A twofold decrease in MPOS current amplitude causes the resistance to decrease to ≤ 20% of the maximum value. The proposed MPOS design makes it possible to lengthen the high-voltage phase and to slow down the repeated closure of the opening switch. The influence of the method of connecting a low-impedance load on the characteristics of a plasma opening switch has been investigated.

1. Introduction

An inductive energy store with a plasma opening switch (MPOS) has benefits to the production of megaampere current pulses with a risetime of ~ 100 ns at a radiating load. All elements of the circuit are placed in vacuum that reduces possible losses. The problem lies in striking a compromise between the required MPOS characteristics and the conditions of energy delivery to a load in a characteristic time of ~ 100 ns. The inductance of the MPOS-load region should be as lower as possible, but it does not always happen that the physical aspects of the MPOS operation [1, 6, 7] allows doing it.

There exist two versions of load connection: A – a traditional circuit with a load located downstream of the opening switch and B – a load is connected upstream of the opening switch. The equivalent circuits of these two versions are shown in Fig. 1. Let us compare the capabilities of both circuits.

The solutions of the system of equations for the circuits presented in Fig. 1 are determined by initial conditions. For simplicity, we assume that at the instant the opening switch resistance begins to increase ($t = 0$), $Iz(0) = 0$, $I1(0) = I1_0 = Ism$, Sz – closed and to the moment the switching is completed ($t \to \infty$, $Is \to 0$) there corresponds the circuit current $I\in$. Under these conditions, the solutions for the transient process have the form:

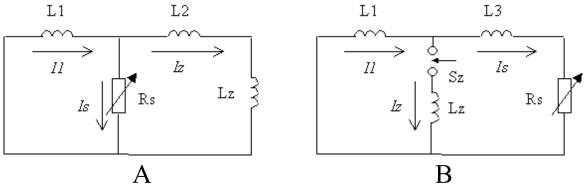

Fig. 1. Circuits of connecting the load Lz: A – load is downstream of the MPOS; B – load is upstream of the MPOS. $L1$, $I1$ – inductance and current of the primary energy store; $L2$, $L3$ – inductance of the MPOS – load region; Rs, Is – resistance and current of the MPOS.

circuit A

$$I\in = I1_0 L1/(L1 + L2 + Lz);$$
$$I1(t) = I\in(1 + h(t)(L2 + Lz)/L1);$$
$$Iz(t) = I\in(1 - h(t));$$
$$Is(t) = I1_0\, h(t);$$
$$h(t) = \exp(-\textstyle\int(Rs(t)/L)dt),$$

where $L = L1(L2 + Lz)/(L1 + L2 + Lz)$;

circuit B

$$I^{*}\in = I1_0 L1/(L1 + Lz);$$
$$I1^{*}(t) = I^{*}\in(1 + h^{*}(t)Lz/L1);$$
$$Iz^{*}(t) = I^{*}\in(1 - h^{*}(t));$$
$$Is^{*}(t) = I1_0\, h^{*}(t);$$
$$h^{*}(t) = \exp(-\textstyle\int(Rs(t)/L^{*})dt,$$

where $L^{*} = L3 + L1Lz/(L1 + Lz)$.

Here $Rs(t)$ is the resistance which arbitrarily varies with time. As follows from the presented relations, the circuit B is more preferable in the case where the characteristics of the opening switch are invariant and the effects of the inductance $L2(L3)$ of the MPOS – load region are tantamount. First, in this version the limiting amplitude of the load current does not depend on the inductance of the MPOS – load region and the achievable value is no less than 90% of $I1_0$. Second, there aren't any stringent requirements on the peculiarities of the MPOS design (the size and form of the electrodes, the size of the plasma region, etc.).

In the general case, the transient process is governed by the value of $Rs(t)$ and by the ratio between $L1$, $L2(L3)$ and Lz. Let us consider a more specific case where $Lz << L1$ (for GIT-12, $Lz \sim 0.1L1$).

Figure 2 shows the calculated curves which allow a comparison of the efficiency of both circuits, depending on the parameter $L2(L3)/Lz$. It can be seen that with the circuit B the time constant of the transient process, which determines the rate of increase in load current, increases simultaneously with increasing the amplitude of the limiting load current. For radiating loads, the occurrence of instability during the shell implosion imposes limitations on the current risetime (it should normally be ≤ 100 ns). These competitive processes, as applied to the GIT-12 parameters and MPOS characteristics, provide the result illustrated by the curve Iz^*/Iz. For an opening switch with $\int Rs(t)dt = 100\ \Omega\cdot\text{ns}$, the current Iz^* of the circuit B at $L2(L3)/Lz \sim 3$ exceeds the current Iz of the circuit A by a factor of ~ 1.07 at the most, whereas the limiting current of the transient process is 1.2 times higher.

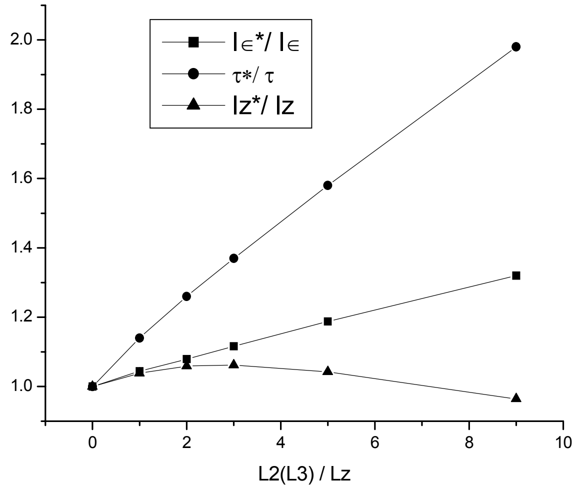

Fig. 2. Effect of the parameter $L2(L3)/Lz$ on the ratios of the limiting amplitudes of the circuit current $I\in$, the time constants τ and the load currents Iz for the circuits A and B(*). (The influence of $L3$ on the amplitude of the current $I1_0$ is taken into account; $Lz = 0.1\ L1$, $\int Rs(t)dt = 100\ \Omega\cdot\text{ns}$)

It should be noted that the circuit A requires protection of the load from MPOS plasma flows. In this connection, practice is to move the load away from the MPOS. This increases the inductance $L2$: in our experiments on the GIT-4 and GIT-12 setups, $L2/Lz \sim 3 \div 5$. The situation with the circuit B is the reverse, it is possible to minimize $L3$ ($L3/Lz \sim 1$). In this case, the current Iz^* of the circuit B may exceed the current Iz of the circuit A by a factor of 1.2÷1.4. The importance of these estimates is beyond question, and therefore the circuit B appears to be of much more practical significance.

Experiments with current switching into a low-impedance load have revealed a decrease in MPOS voltage and a rapid drop in MPOS resistance both for the circuit A [1, 7] and for B [4]. This is explained by the decrease in the energy evolved in the MPOS which goes, among other things, into removing the plasma from the switch zone and also by the drop of the magnetic pressure acting on the plasma surface. For the circuit B the moment of switching to the load is of importance [3]. The MPOS resistance should reach the required values before the instant the current and the magnetic field in the MPOS start to decrease due to current switching to the load. Moreover, there should be effective current switching within the time the opening switch is in the high-resistance state. This fact is not a priory apparent because of the self-consistent behavior of the MPOS resistance and magnetic field at the MPOS cathode, as revealed experimentally [1, 5].

In this work we studied the influence of current switching to a low-impedance load on the MPOS characteristics in the circuits A and B.

2. Experimental Procedure

For an adequate comparison of the characteristics of different MPOS's, one should use identical initial conditions and choose a proper method of experimental data processing and representation. To attain these ends, most of our experiments were performed with the same arrangement. This arrangement is shown in Fig. 3 and its detailed description can be found elsewhere [3]. Here we only note that an ordinary coaxial MPOS(S0) was realized by installing an opaque screen on the cathode rods. The load in the circuit A is a short-circuited coaxial with a current IzA. For the circuit A and for no-load conditions, elements 3 and 4 were not used.

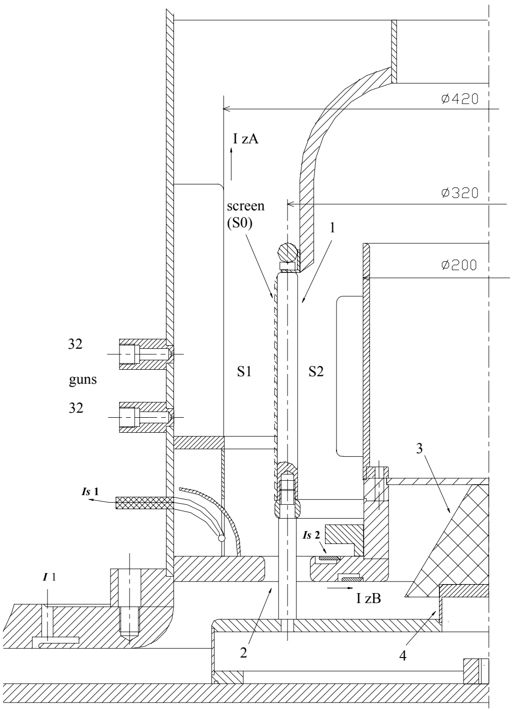

Fig. 3. Design of the device: 1 – cathode, 2 – post-hole convolute, 3 – insulator of the closing switch and 4 – load for the circuit B

Data were processed and represented by the procedure illustrated in Fig. 4. For each shot the curve $Is(t)/Ism = f(t)$ ($Ism = I1_0$, $Is(t) = I1(t) - Iz(t)$) normalized to the maximum current was plotted. Using the calculated curve $Rs(t)$, graphical integration was made for the time intervals Δt_i, which corresponded to the change of the switch current by $\Delta Is(t) = 0.1Ism$. The average resistance Rsi within the time Δt_i was determined from the expression $Rsi = \int_{\Delta ti} (Rs(t)dt)/\Delta t_i$. The maximum calculated value of Rsi is denoted as Rsm. The thus obtained data were employed in plotting the dependence of the normalized resistance Rs/Rsm on the normalized current $Is(t)/Ism$. Each point of the plot was determined by averaging Rsi/Rsm over several shots.

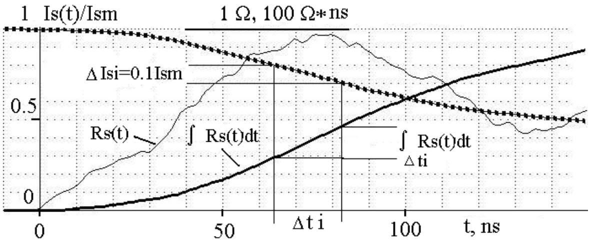

Fig. 4. Method of experimental data processing

3. Results

For practical use of the circuit B, one should ascertain the degree to which leading part of the current from the POS region influences the POS characteristics during the high-voltage phase. In this connection, we have performed experiments on the GIT-12 setup. The electric circuit and experimental conditions are described in detail in [3]. The results for the coaxial MPOS (S0) are presented in Fig. 5. To construct plot 1, we also used the findings obtained earlier with a similar geometry of the opening switch electrodes [1, 6].

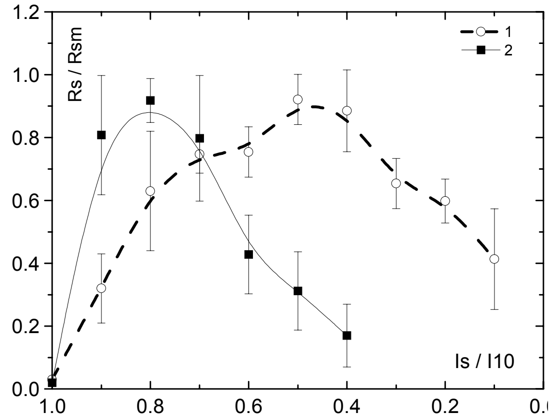

Fig. 5. The normalized resistance of the coaxial MPOS (S0) versus the normalized current ($Lz = 15 \div 25$ nH): 1 – circuit A, 2 – circuit B

These plots allow us to state that switching part of the current from the MPOS region to the load located upstream of the opening switch with associated decrease in magnetic field at the cathode causes the MPOS to close more rapidly. This decreases the efficiency of energy delivery to the load. In this mode, the amplitude of the load current is substantially lower than the value, which corresponds to the transient process in the circuit B $I_{Lz} \cong I1_0L1/(L1 + Lz)$. In addition, we would like to note that in the circuit A (plot 1) the variation in the load inductance Lz from 20 nH to 50 nH scarcely affected the character of the curve.

To slow down the closing of the opening switch, a MPOS (S1 + S2) design with a rod cathode transparent to plasma and with vane anodes was proposed [3]. The MPOS (S1 + S2) operation has some peculiarities untypical for the design with a solid cathode (S0). These peculiarities manifest themselves during no-load operation under identical conditions. Besides the switching of the current from one-half the switch to the other due to possible nonsynchronous opening (Ref. [7] and Fig. 6), the adjacent electrode gaps affect the conductivity of each other. As is seen from the oscillograms in Fig. 6, the conductivities of the gaps S1 and S2 vary such that the full time the MPOS is in the high-voltage state is increased. The plots in Fig. 7 support the fact that with (S1 + S2) the opening switch closes slower, as compared to S0.

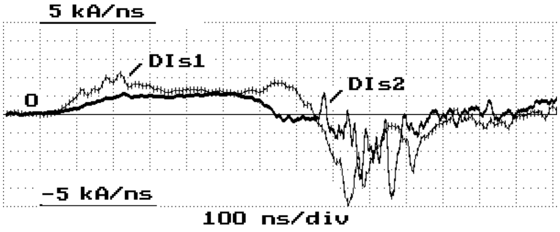

Fig. 6. Waveforms of the current derivative taken from the sensors *DIs*1 and *DIs*2 for the MPOS (S1 + S2) design in no-load conditions

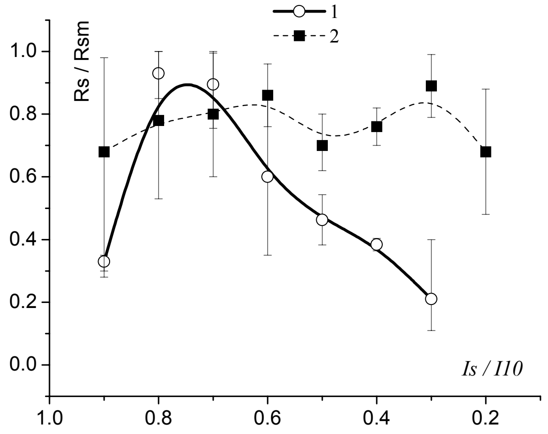

Fig. 7. Normalized MPOS resistance versus the MPOS normalized current in no-load conditions: 1 – MPOS (S0); 2 – MPOS (S1 + S2)

This positive property of the MPOS (S1 + S2) design is essential to the operation of the circuit B. Figure 8 shows the characteristics of both MPOS versions on current switching to a low-impedance load of 15–25 nH for the circuit B. It can be seen that the MPOS (S1 + S2) remains open when the MPOS current is decreased to ≤ 0.2 *Ism*.

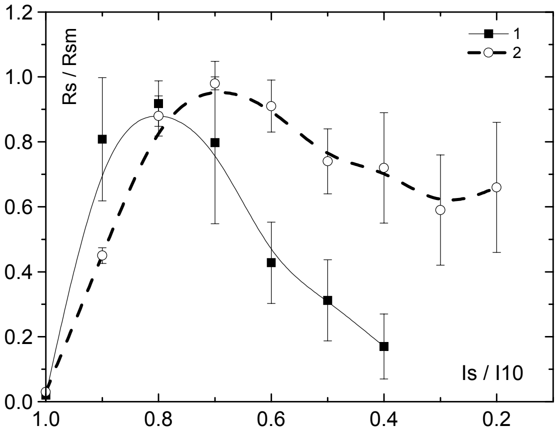

Fig. 8. Normalized resistance versus the current of the circuit B (Lz = (15–25) nH): 1 – MPOS (S0); 2 – MPOS (S1 + S2)

4. Conclusion

The obtained results indicate that the duration of the high-voltage phase of the opening switch depends heavily on its magnetic field. For the version B where the current switched to the load leaves the region of the opening switch, there is a decrease in load current amplitude, as compared to the limiting amplitude of the completed transient process. In the designed opening switch [3], we have managed to decrease the influence of the processes resulting in repeated closure of the MPOS. In the MPOS (S1 + S2) version, the resistance makes up ~ 50% of the maximum value, even with a fivefold decrease in current amplitude. This finding together with the positive effect observed in experiments with a controllable closing switch [3] allows an optimistic estimate of the capabilities of the circuit B for the use in experiments with a radiating load.

References

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