Study of a Plasma Opening Switch in Current Switching to a Coaxial Line with Short-Circuited and Open-Circuited Central Conductors

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Abstract – A plasma opening switch (POS) with radial plasma injection has been investigated on the GIT-4 generator. The extension of the plasma-filled region by the beginning of the high-voltage phase has been estimated for different delay times between the generator triggering and the operation of plasma guns. It has been shown that if the central electrode of the POS runs the entire length of the plasma-filled region the abrupt voltage rise is due to the arrival of the magnetic field front at the plasma-vacuum interface and if it passes only through part of the injected plasma, the abrupt voltage rise owes to the entry of the magnetic field front into the region of the face of the central electrode.

1. Introduction

In pulsed generators with an inductive energy store and plasma opening switch there are two methods of connecting the transmission line to a load. With the first method, the transmission line is immediately downstream the switch and its electrodes are an extension of the POS electrodes. The second method is based on spatial separation of the POS and transmission line regions and the load is connected upstream the POS [1]. In this event, the central electrode of the switch is open and passes through part of the injected plasma only.

The GIT-4 generator [2] was used to study experimentally the penetration of a magnetic field into the POS plasma and the mode of current switching for the cases where the extension of the central conductor of the switch was absent or formed a short-circuited coaxial line.

2. Experimental Arrangement

The arrangement employed in experiments is shown in Fig. 1. Thirty two capillary plasma guns [2] are located on the outer conductor and inject plasma in the radial direction. The guns is powered by two IK-50-3 capacitors (16 guns per capacitor) charged to 40 kV. In the first half-cycle the amplitude of the discharge current though a gun is ~9.5 kA, the time in which the first maximum is reached is ~1.4 μs. In the region of injection the cathode electrode is conical in shape and its diameter in the plane of plasma guns is 110 mm. Downstream the POS there is a camera with eight B-dot probes $a1$–$a8$. The distance between adjacent probes is 40 mm and that from the injection plane to the first probe is 250 mm. The inductance from a vacuum insulator to the injection plane $L_v \sim 138$ nH.

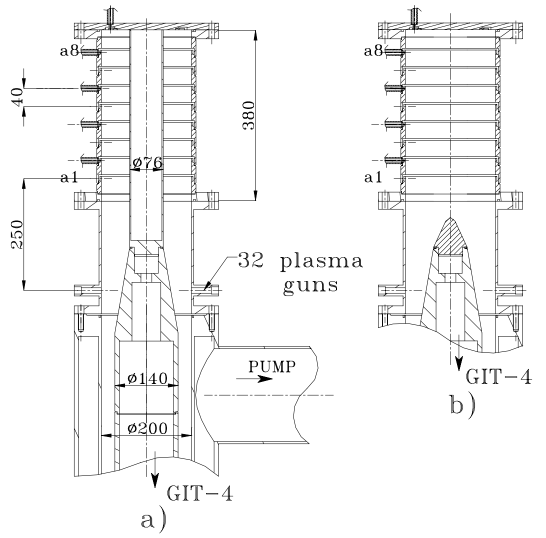
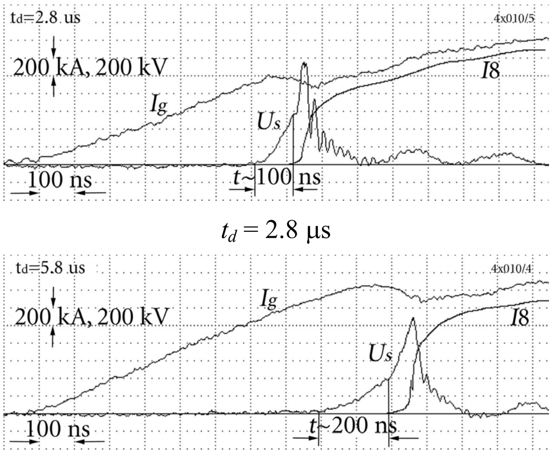


Fig. 1. Experimental arrangement used in studies of current switching downstream the POS

In the first version (Fig. 1, a) the load is formed by a ∅76-mm central conductor and a ∅200-mm external cameral. The load inductance from the plasma injection plane is ~108 nH. In the second version (Fig. 1, b) the central conductor of the load coaxial is replaced by a conical neck of length 65 mm. The inductance from the insulator to the cathode face is ~170 nH. The voltages across the vacuum insulator U_r was measured by an active divider, the total generator current I_g by a Rogowskii coil and the current switched downstream the POS $I1$-$I8$ by B-dot probes.

3. Results of Experiments

Figure 2 shows waveforms of the generator current I_g, current from the farthest inductive pickup $I8$, and rated POS voltage in the injection plane $U_s = U_r - L_v \cdot \dfrac{dI_g}{dt}$ for a short-circuited central electrode and times delay of 2.8 and 5.8 μs. At t_d = 2.8 μs the current of the generator circuit increases to ~1 MA in a time of ~0.8 μs. A signal from the probe most distant from the plasma injection plane appears within ~100 ns after the rise of the voltage U_s. The delay time ~100 ns characterizes the time it takes for the magnetic field to penetrate from the injection plane to the end of the load line. Increasing the time delay to 5.8 μs causes the current to increase to ~1.4 MA and the conduction time lengthens to ~1 μs. The time in which the magnetic field penetrates from the injection plane to the end of the load line increases two times (to ~200 ns). In both cases, the current is almost completely switched to the load. The instant the voltage shows an abrupt increase corresponds to the moment a signal arrives from the eighth probe.



$t_d = 2.8$ μs

$t_d = 5.8$ μs

Fig. 2. Waveforms for the experiment with a short-circuited central electrode

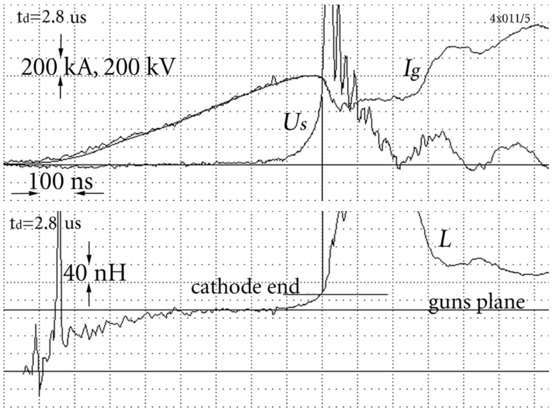
At $t_d = 2.8$ μs, the delay between signals from the first and eighth probes is ~20 ns. The signals from the farthest five probes appear nearly at a time. Consequently, in this part of the load coaxial the electromagnetic wave travels with a velocity close to the velocity of light and the plasma is absent here. As the time delay is increased to 5.8 μs the delay between signals from the first and last probes increases to ~55 ns. Delays are observed between all eight signals. Hence, the whole of the load coaxial is filled with plasma. The average velocity of the magnetic field in the probe region is $\sim 5 \cdot 10^8$ cm/s.

Taking the axial coordinate of an B-dot probe, from which signals start to appear almost at a time, as a conditional plasma vacuum interface, the latter is ~33 cm away from the injection plane at $t_d = 2.8$ μs and at $t_d = 5.8$ μs it is ~53 cm removed from. This motion of the leading plasma boundary corresponds to an average velocity of $\sim 6 \cdot 10^6$ cm/s. Here we imply plasma of density corresponding to penetration of the magnetic field $B \sim 5$ T with a velocity of $\sim 5 \cdot 10^8$ cm/s. From the expression for the KMC shock wave velocity of penetration of the magnetic field [3]:

$$u_H = \frac{B(t)\alpha}{\mu_0 enr}, \ \alpha = 1 + \frac{r}{2n}\frac{\partial n}{\partial r} \sim 1$$

the plasma density is estimated as $n \sim 10^{14}$ cm^{-3}.

Figure 3 shows waveforms of the generator current I_g, rated POS voltage in the injection plane U_s, and rated inductance to the point of shortening the current channel $L = \frac{\int U_r dt}{I_g}$ in the experiment with an open-circuited central electrode for $t_d = 2.8$ μs. It is seen from the presented dependence of the inductance that the main duration of the conduction phase is dictated by the penetration of the magnetic field into the region of the plasma guns where the plasma density is maximum. The inductance obtained in the experiment at the moment of the abrupt voltage rise corresponds to that calculated from the system geometry assuming shortening to the cathode face.



$t_d = 2.8$ μs

Fig. 3. Waveforms for the experiment with an open-circuited central electrode

Figure 4 shows signals from inductive probes 2, 4, 6, and 8 at $t_d = 2.8$. The amplitude of signals from probes distant from the injection plane ($a6$, $a8$) decreases. According to the results of experiments with a short-circuited load the region where these probess are located is free from plasma. As the time delay is increased to 5.8 μs, when the camera with B-dot probes is filled with plasma throughout the length,

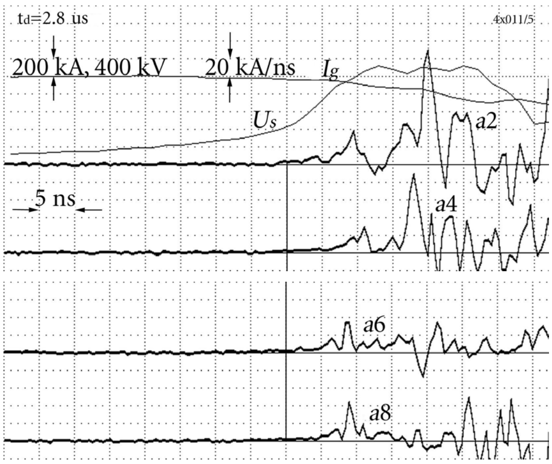


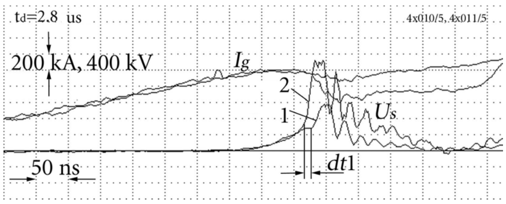
Fig. 4. Signals from the B-dot probes at $t_d = 2.8$ μs

the amplitude of signals from all probes is held approximately at one level. Signals from all probes appear nearly at a time, no matter what the time delay is.

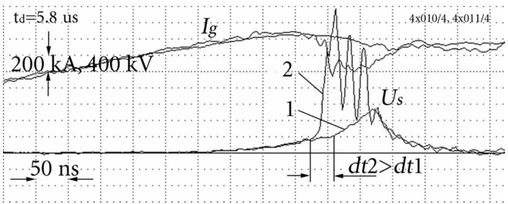
With an open-circuited central conductor, the magnetic field is carried into the region of the cathode face by the electron flow propagating along the system axis. If there is a gradient of the plasma density along the system axis in the region of transportation, part of the electron flow is shorted to the wall of the outer conductor of the coaxial and only that part which can be passed through the region at the end of the transmission line reaches the anode face electrode. Therefore, the level of signals from the farthest pickups decreases with decreasing time delay.

4. Discussion of the Results

Figure 5 presents the superimposed waveforms of the generator current I_g and POS voltage U_s for experiments with a short-circuited and open-circuited central electrode. It can be seen that the time the voltage rises and its initial portions coincide. Differences begin to appear only where the magnetic field approaches the region with different geometries of the central electrode. For the open central electrode the maximum voltage is higher and the time in which it is reached is smaller, as compared to the short-circuited load.



t_d = 2.8 μs



t_d = 5.8 μs

Fig. 5. Comparison of experimental results for a short-circuited (1) and open-circuited (2) coaxial

In the case of a cylindrical conductor of diameter 76 mm the magnetic field continues to penetrate with an outlet velocity along the short-circuited coaxial in the form of a KMC shock wave. In so doing, the time of penetration depends on the distance form the plasma-vacuum interface and, thus, on t_d. With the open central electrode, the voltage starts rising abruptly when the magnetic field front penetrates to the cathode face, regardless of the plasma-vacuum interface position (if the boundary is beyond the plane of the cathode face). Therefore, *dt* between steep portions of the voltage for the short-circuited and open-circuited coaxials increases with increasing time delay (Fig. 5).

5. Conclusion

In a POS with radial injection and a 5.8-μs delay of the generator triggering the plasma boundary by the moment the high-voltage phase begins is ~0.5 m away from the plane of plasma guns. In this part of the coaxial the plasma of density $\sim 10^{14}$ cm^{-3} axially expands with an average velocity of $\sim 6 \cdot 10^6$ cm/s

With the central POS electrode passing throughout the length of the plasma-filled region the abrupt voltage rise across the switch is due to the penetration of the magnetic field front to the plasma-vacuum interface.

In the case where the central electrode of the switch is open and its length is smaller than the plasma-filled region, voltage rises abruptly because the magnetic field front reaches into the plane of the cathode face, no matter what the position of the plasma-vacuum interface is.

References

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