On the Plasma Opening Switch Peak Voltage

S.V. Loginov

Institute of High Current Electronics SD RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia
loginov@oit.hcei.tsc.ru

Abstract – A simple analysis of the basic types of circuit for inductive energy storage using a plasma opening switch has been performed. Formulas which can be used to estimate the peak switch voltage and the time it takes for this voltage to peak, depending on the switch resistance rise rate, are given. For high voltages, the switch resistance rise rate, $\dot{R}_s \approx 300\frac{v_d}{r}$, is determined by the directional plasma velocity, v_d, and by the cathode radius r. For low voltages, the resistance rise rate also depends on the switch current I_s, on the current rise rate, $\dot{I}$, and on the switch length, L: $\dot{R}_s \approx 2.25\cdot 10^5 \frac{v_d}{g^2(r)r}\frac{L\dot{I}}{cI_s}$.

The design principles for generators with inductive energy storage and a plasma opening switch are discussed in [1]. These generators are attractive due to their design and cost advantages over capacitive energy stores. They are realizable owing to the switch ability to pass a rather high current in the conduction phase and then cut it off within a short time [2]. In the conduction phase of the switch operation, the inductor of the generator is charged by a current I_0. As the switch opens, it carries a voltage whose value depends on the parameters of the circuit and on the switch resistance rise rate.

If the switch itself serves as a load (Fig. 1, *a*), the current in the circuit after its opening is given by

$$I_s = I_0 \exp\left(-\int_0^t \frac{R_s(t)}{L_g}\mathrm{d}t\right).$$

Since the current drops exponentially, the switch voltage, $V_s = I_s R_s$, peaks on condition that

$$\dot{R}_s(t) = R_s^2(t)/L_g. \tag{1}$$

If the switch resistance increases linearly, $R_s(t) = \dot{R}_s t$, the switch voltage reaches a peak value

$$V_m = I_0\sqrt{\dot{R}_s L_g}\,e^{-1/2} \tag{2}$$

at a time

$$t_m = \sqrt{L_g/\dot{R}_s}. \tag{3}$$

For $\dot{R}_s$ = 0.1 kA/ns and I_0 = 1 MA, as L_g is increased from 100 to 400 nH, t_m increases from 32 to 63 ns and the switch voltage increases from 1.9 to 3.8 MV.

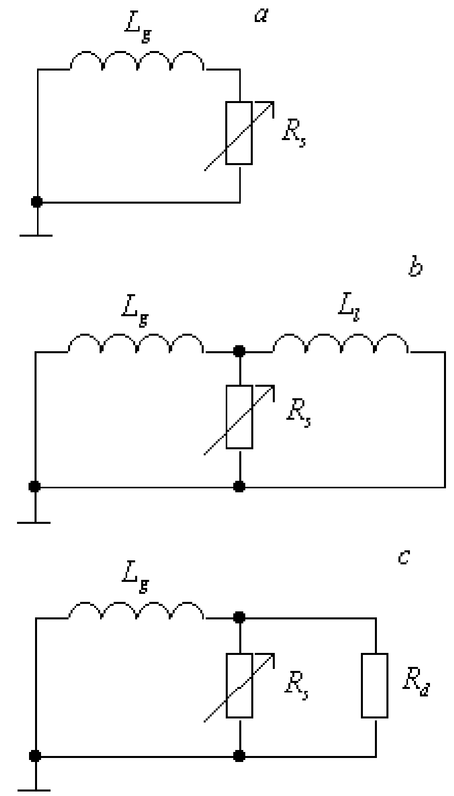

Fig. 1. Basic types of circuit with a plasma opening switch

For the circuit design where an inductive energy store carries an inductive load (Fig. 1, *b*), the switch current is given by

$$I_s = I_0 \exp\left(-\int_0^t \frac{R_s(t)}{L_t}\mathrm{d}t\right)$$

and the load current by

$$I_l = I_0 \frac{L_g}{L_g + L_l}\left(1 - \exp\left(-\int_0^t \frac{R_s(t)}{L_t}\mathrm{d}t\right)\right),$$

where

$$L_t = \frac{L_g L_l}{L_g + L_l}$$

is the equivalent inductance. For this circuit design, the peak switch voltage and the time it takes for the voltage to peak are determined by the equivalent inductance L_t. To the case where the energy delivered to the load is a maximum there corresponds the equality of the store and load inductances: $L_g = L_l$. For this case, we have $L_t = 0.5L_g$, and t_m and V_m decrease by a factor of $\sqrt{2}$ compared to the respective parameters of the switch in no-load operation.

In the circuit design where an opening switch operates into a diode of invariable impedance (Fig. 1, *c*), the current in the switch is given by

$$I_s = I_0 \exp\left(-\int_0^t \frac{L_g \dot{R}_s(t) + R_s(t) R_d}{L_g (R_s(t) + R_d)} dt \right).$$

The condition for the voltage to peak formally coincides with (1), and, hence, the voltage rise time and amplitude do not depend on the diode impedance. However, the actual switch resistance rise rate in the case of a low-impedance diode may be considerably smaller than in the case of a high-impedance load, and the switch voltage will depend on the load impedance.

It is of interest to compare the values of V_m and t_m predicted by formulas (2) and (3) with experimental data. In the experiment described in [3], the discharge current of a capacitor into an inductor of inductance 0.7 μH reached ~ 75 kA, and as an opening switch operated, this current was switched into an inductor with an inductance equal to the storage one. The resistance of the switch increased to ~ 16 Ω in 50 ns; the switch voltage reached 400–500 kV. According to (2) and (3), for $L_g = L_f$, the switch voltage should increase to 480 kV in ~30 ns. In experiments on the Marina generator [3], the current in an inductor of inductance 1.3 μH reached 250 kA and then it was switched into an inductor of inductance 0.8 μH. The switch resistance increased at a rate of 0.8 Ω/ns and reached 16 Ω in 20 ns. The switch voltage increased to 2.5 MV. From (2) and (3) it follows that the voltage should reach 3 MV within 25 ns, which agrees with the experimental result. In the proof-of-principle experiment described in [4], the current in an inductor of inductance 150 nH increased to 80 kA and then it was switched into an inductor of inductance 15 nH within 30 ns; hence, the switch voltage was ~ 40 kV. For t_m = 15 ns, from (3) it follows that the resistance rise rate should be ~ 60 mΩ/ns, and from (2) that the voltage should be ~ 47 kV.

The above examples show that the expected switch voltage and the time it takes to achieve this voltage can be estimated based on the switch resistance rise rate if the latter is known with a fair degree of confidence. According to the mechanism of current cutoff proposed in [5], the switch resistance is governed by the erosion gap that is formed as the current channel arrives at the end of the previously created plasma bridge far from the generator. The erosion gap length l_s must be chosen such that the switch current

$$I_s = \left(6\pi m_i c^2 n / Z\right)^{1/4} \left(\frac{\dot{I}^2 r^2 L^2}{g(r)} \right)^{1/4}$$

would pass in the bipolar mode [6, 7]. Here,

$$g(r) = \frac{\ln R/r}{(R/r)^2 - 1},$$

r and R are the cathode and anode radii, respectively; L is the opening switch length; $\dot{I}$ is the switch current rise rate; m_i and Z are the mass and charge number of the plasma ions; n is the plasma density, and c is the velocity of light. For the velocity of magnetic field penetration, u, being of the order of the Alfven velocity, the formative time of the gap is given by

$$t_s = \frac{l_s}{u} = \frac{3}{2}\frac{mc^2}{e}\left(\frac{m_i}{Zm}\right)^{1/2} \frac{\dot{I}rL}{g(r) v_\mathrm{d} I_s^2},$$

where v_d is the velocity of the directional motion of the plasma ions. The minimum width of the erosion gap formed in the switch plasma within this time is

$$d_m = v_\mathrm{d} t_s f\left(\frac{l_s}{\Delta}\right),$$

where $f\left(l_s/\Delta\right) \sim 5$ for $l_s/\Delta \sim 50$–100 [8]. For a magnetically insulated gap, the switch current and voltage V_s are related as

$$I_s \cong \frac{mc^3}{2e}(\gamma^2 - 1)^{1/2}\frac{r}{d_m},$$

where $\gamma = 1 + eV_s/mc^2$. In view of this relation, for high voltages, the switch resistance is

$$R_s = 60\frac{d_m}{r},$$

and the rate of its rise,

$$\dot{R}_s[\Omega/s] \approx 300\frac{v_\mathrm{d}}{r}, \tag{4}$$

is determined only by the directional plasma velocity and by the cathode radius. For typical values of v_d ~ 2–20 cm/μs and r ~ 5 cm, the resistance of the opening switch increases with a rate $\dot{R}_s$ ~ 0.1–1 Ω/ns.

For low voltages, the switch resistance is given by

$$R_s = 60\frac{I_s}{mc^3/e}\frac{d_m^2}{r^2}.$$

The rate of its rise, determined as

$$\dot{R}_s[\Omega/s] \approx 2.25\cdot 10^5 \frac{v_\mathrm{d}}{g^2(r)r}\frac{L\dot{I}}{cI_s} \quad (5)$$

in contrast to (4), depends on the switch current and its rate of rise and on the switch length. For the conditions of the experiment described in [4]: I_s = 75 kA, $\dot{I}$ = 4.5·10^{10} A/s, L = 20 cm, and r = 1.5 cm, the resistance rise rate is estimated to be 0.5 Ω/ns, which coincides in order of magnitude with experimental data.

Thus, formulas (4) and (5), which relate the resistance rise rate to the switch parameters, allow one to estimate with a reasonable accuracy, by using relations (2) and (3), the expected switch voltage and the time it takes for the voltage to reach this value.

References

[1] B.M. Kovalchuk, G.A. Mesyats, Dokl. AN SSSR **284**, 857 (1985).

[2] Special Issue on Fast Opening Vacuum Switches, IEEE Trans. Plasma Sci. **15** (1987).

[3] G.A. Mesyats, S.P. Bugaev, A.A. Kim et al., IEEE Trans. on Plasma Sci. **15**, 649 (1987).

[4] D.D. Hinshelwood, J.R. Boller, R.J. Commisso et al., Appl. Phys. Lett. **49**, 1635 (1986).

[5] S.V. Loginov, Pis'ma Zh. Tekh., Fiz. **29**, 14 (2003).

[6] W. Rix, D. Parks, J. Shanon et al., IEEE Trans. Plasma. Sci. **19**, 400 (1991).

[7] B. Cassany, P. Grua, J. Appl. Phys. **78**, 67 (1995).

[8] S.V. Loginov, "Gap formation in microsecond megaampere plasma opening switches", presented at *13th Symposium on High Current Electronics*, Tomsk, Russia, 2004.