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TITLE: FAST EXPLOSIVE-DRIVEN OPENING SWITCHES CARRYING HIGH LINEAR CURRENT DENSITIES

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FAST EXPLOSIVE-DRIVEN OPENING SWITCHES CARRYING HIGH LINEAR CURRENT DENSITIES[*]

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ABSTRACT. Experiments are being conducted on switches similar to those described by Pavlovskii et al. where large currents are interrupted in an inductive store by explosively compressing a current-carrying plasma channel. We have used capacitor banks and explosive-driven magnetic-flux-compression generators to produce linear current densities of $\leq$ 0.6 MA/cm in the plasma channel. Resistances that increase exponentially with e-folding times of 200 to 400 ns are obtained in these experiments. Data from these experiments are presented, along with calculations showing the advantages of using this technique in explosive-plate-generator-driven circuits.

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1. INTRODUCTION

Many applications for pulsed power technology require current pulses of shorter duration than those available by directly coupling an explosive generator to a load. Figures 1 and 2 show circuits that provide short pulse capabilities when used in conjunction with explosive generators. In each of these circuits the switch, S_3, is closed at the appropriate time to deliver the desired length pulse. Inefficiencies in the operation of these circuits for very short pulse lengths (< 1 μsec), however, lead us to examine the advantages offered by the circuit shown in Fig. 3, where the switch, S_4, opens against the current flowing through it. The closing of S_3 is coordinated with the opening of S_4 to allow an appropriate length pulse to be delivered to the load. A variety of fast opening switch concepts have been explored, but the most attractive for our purposes appears to be that described by Pavlovskii et al. [1]. In this technique, current flows in a relatively low resistance plasma cavity. The opening switch action occurs when high pressure explosives products are suddenly introduced into the cavity driving the resistance up. We are currently performing experiments to characterize such devices for operation in the pulsed power regime compatible with our generators and requirements.

2. THE PULSED POWER REGIME

We expect to use opening switches with classes of generators that operate normally in a few tens of microseconds. In order to achieve large currents, these generators may be boosted by an additional generator that provides a very high initial field and has a pulse duration of a few hundred microseconds. For the applications of our generators where switches are needed, we expect to require pulses of < 1 μsec. Because of the high ratio of total pulse length to load pulse length, opening switches that can carry current indefinitely are preferable.

In addition to the time compression requirement, a high current density capability is highly desirable. Many of our generators operate at near 1 MA/cm linear current density, and in order to make the size of the switch commensurate with the generator size, switches that operate at large current densities are necessary. Pavlovskii's published results [1] are at a linear current density of 0.1 MA/cm, and Turman et al. [2] have explored the concept up to 0.2 MA/cm. We are currently performing experiments in the range up to 0.6 MA/cm.

3. EXPERIMENTAL SETUP

Figure 4 illustrates the parallel plate geometry we have used in the tests we describe. Current flows in a planar cavity that is ~ 3 cm wide and 5 cm long or ~ 6 cm wide and 2.5 cm long. We have some difficulties with this geometry that are not present in the geometry used by Pavlovskii. Principally, pinching occurs in the plasma cavity, and high voltage breakdown paths around the sides of the electrodes are difficult to eliminate. However, we are able to perform many tests with this setup quickly and at a low cost.

For many of our tests, we have used a 2,500 μF capacitor bank at 15 kV to provide currents of ~ 1 MA to the plasma cavity (linear current density of ~ 0.3 MA/cm). For tests at higher current densities ($\leq$ 0.6 MA/cm) we have used parallel plate explosive generators.

4. EXPERIMENTAL RESULTS

Most of our experiments have been performed with the objective of observing the resistance rise as PBX 9501 explosive products are introduced into the cavity. In these tests, maximum voltage develops since no parallel load is switched into the circuit when the resistance begins to rise. Our test assembly does not allow us to develop more than ~ 50 kV in the circuit, but this level was reached in both capacitor bank and plate generator powered experiments.

Figure 5 shows the resistance rise attained in a capacitor bank experiment. In this test the current density was 0.3 MA/cm, and when the system limit of ~ 50 kV was reached, the resistance had increased by a factor of ~ 7. The peak voltage drop across the switch was only ~ 10 kV/cm.

Figure 6 shows the resistance rise attained in a plate generator experiment. The current density in this test was 0.5 MA/cm. The plasma cavity was half the length of the plasma cavity used in the previously described capacitor bank driven experiment, so when the limit of ~ 50 kV was reached, the voltage drop across the plasma was ~ 20 kV/cm. At this time, the resistance had increased only a factor of ~ 4.

The magnitude of the resistance rise in these experiments is not high, but because there were extraneous breakdown problems, the peak resistances attained do not represent limits. Further experiments with systems capable of withstanding more than 50 kV will be required to determine the ultimate resistance achievable at these current densities. What is encouraging in these data is that, in spite of the elevated current densities, resistance increases occur on a time scale of interest.

5. APPLICATION OF EXPLOSIVE PLATE GENERATOR CIRCUITS

Plate generators are a type of explosive generator distinguished by maintaining a high driving impedance until burnout, the time when flux compression is complete. Although the peak resistances developed are modest in the opening switch tests described, with no further improvements they are high enough to provide some benefit in experiments conducted using plate generators. Figure 7 shows plots of (dL/dt) and L versus t for one of our explosive plate generators. Since the units of dL/dt are milliohms, it can be seen that dL/dt represents the driving impedance of the generator. Loads with impedance < |dL/dt| of the generator can be powered directly by this generator. For loads meeting this requirement and requiring short pulses, an opening switch is beneficial if it will carry current efficiently during the early operation of the generator, then jump to some higher resistance on command.

Figure 8 is a circuit used for computer simulations of explosive generator tests. In this simulation, L_G is the explosive plate generator with the dL/dt and L shown in Fig. 7. The opening switch is represented as a resistor that remains fixed at 4 mΩ until the last 1.25 μsec of the generator operation, then increases linearly for 0.5 μsec to 40 mΩ where it remains fixed until generator burnout. The switch, S_1 closes 0.25 μsec after the resistance begins to increase, allowing current to flow to the load for the last 1 μsec of generator operation. The results of simulating the final 1.5 μsec of generator operation are shown in Fig. 9. The current in the simulated switch is ~ 2.6 MA when it begins to open, and ~ 3 MA is delivered to the load in 1 μsec.

Higher final resistances in the switch offer better efficiency, of course, but the advantage gained even at this resistance is illustrated in Fig. 10, where the same simulation is reproduced with the exception that the opening switch resistance is never allowed to increase. In this case, it is seen that the generator develops considerably more current, (6.6 M' rather than 5 MA) but only delivers 1.7 MA to the load. For an additional comparison, we ran a simulation of the technique illustrated in Fig. 2. Using the same generator, load and initial conditions as in the previous two calculations, 2.4 MA was the largest pulse that could be delivered to the load.

If the plate generator in Fig. 8 is replaced by a static storage inductor, then we can simulate a more conventional application of opening switches. These calculations represent the use of our opening switches in circuits where the explosive generator has been used to charge a storage inductor, but has burned out or has only a negligible dL/dt when the load is switched into the circuit. A complete discussion of the inductive storage current transfer process is beyond the scope of this paper, and the reader is referred to Reinovsky et al. [3] for a more complete treatment. As a basis for comparison, however, we ran simulations with the same amount of stored inductive energy as available in a plate generator at an equivalent time relative to the load pulse. In our first case, the current and storage inductance are set equal to the corresponding plate generator parameters when the current transfer process begins. The load and switches remain identical. In this case, only about 1.4 MA are transferred to the load in the first microsecond. For additional comparisons, we simulated the same inductive storage circuit but increased the peak resistance.

Optimum 1-μsec pulses require only 75 mΩ switch resistance, and if peak resistance is 200 mΩ, the risetime drops to ~ 0.5 μsec. However, only approximately 1.5 MA are delivered to the load in these cases. Finally, Fig. 11 shows the result of a simulation where the initial current and peak opening switch resistance are adjusted to deliver 3 MA to our standard simulation load in 1 μsec. To obtain a 1 μsec risetime, a 75 mΩ opening switch is required. The total stored inductive energy in this simulation is 660 kJ as compared to 211 kJ in the plate generator simulation that delivered the same pulse to the load.

What these examples demonstrate is that, given a fixed amount of inductive energy stored in a circuit and a fixed risetime of the current pulse, the largest current pulse is delivered by the explosive plate generator in conjunction with a very modest resistance opening switch.

We note that, in a pure inductive store process, higher resistance switches provide faster pulses to the load, but the only way to deliver the same amount of current from a strictly inductive store is to increase the total stored energy.

6. CONCLUSIONS

We believe that the peak-resistance values observed in our preliminary opening switch tests are not the largest that can be obtained. Experiments capable of withstanding larger voltage will be performed to determine what the real peak resistance limits are. We have, however, demonstrated that we can achieve a resistance rise in circuits carrying high current densities that is high enough to allow us to produce larger short current pulses into our load than we can deliver without such a switch.

In addition, using these switches with explosive plate generators can provide larger short pulses for a given stored inductive energy than are available from pure inductive storage techniques.

REFERENCES

[1] PAVLOVSKII, ET AL., Sov. Tech. Phys. Lett. 3, 320 (1977).

[2] TURMAN, B. N., ET AL., Megampere Current Experiments with the Intrepid Fast Opening Switch, Sandia National Laboratories Report SAND-82-1531 (1982).

[3] REINOVSKY, R.E., ET AL., IEEE Transactions on Plasma Science, Vol. PS-10, No. 2 (1982) 73.

FIGURE CAPTIONS

Figure 1. A short pulse can be obtained from an explosive generator (L_g) by coupling the load to the output of the generator through a transformer. The length of the pulse is determined by the closure time of S_3.

Figure 2. A short pulse can be obtained from an explosive generator (L_g) by using a ballast inductor (L_B) to complete the generator circuit during the early time operation of the generator, then closing the switch, S_3, at the appropriate time. L_B must be optimized according to the load, generator and length of pulse desired.

Figure 3. In short pulse applications, more efficient use is made of the explosive generator (L_G) if an opening switch (S_4) is used in the generator circuit during early stages of generator operation. The relative timing of closing S_3 and opening S_4 is adjusted according to switch characteristics.

Figure 4. Parallel plate opening switch geometry. The arrows in the side view show how current flows in the plasma cavity and the end view shows how the plasma is confined at its edges by the quencher.

Figure 5. Resistance rise obtained in a capacitor bank powered experiment where the linear current density in the plasma cavity was 0.3 MA/cm.

Figure 6. Resistance rise obtained in an explosive plate generator powered experiment. Linear current density at switch time was 0.5 MA/cm.

Figure 7. Inductance (L) and dL/dt curves for a typical explosive plate generator. L is the solid line and dL/dt is the dashed line.

Figure 8. Circuit used to simulate the operation of an explosive plate generator (L_G) delivering a short pulse to a load with the aid of an opening switch. The opening switch is modeled as a resistor that increases linearly between prescribed end points for a fixed time interval.

Figure 9. Results of simulating the circuit shown in Fig. 8. The solid line is the total generator current, the dotted line is the load current and the dashed line is the current in the switch. The switch resistance begins to rise at 12.75 μsec and generator burnout occurs at 14 μsec.

Figure 10. Results of simulating the circuit shown in Fig. 8. In this case, the switch resistance was never increased. The solid line is generator current, the dotted line is load current and the dashed line is switch current. Comparing to Fig. 9 shows

that the generator develops more current, but much less is delivered to the load.

Figure 11. A 60 nH storage inductor carrying about 4.7 MA will deliver 3 MA to our simulation load in 1 μsec with the aid of a 75 mΩ opening switch. This compares to the plate generator simulation of Fig. 9, where the generator was carrying about 2.6 MA, at an inductance of 60 nH, and delivered 3 MA to the load in 1 μsec with the aid of a 40 mΩ opening switch.

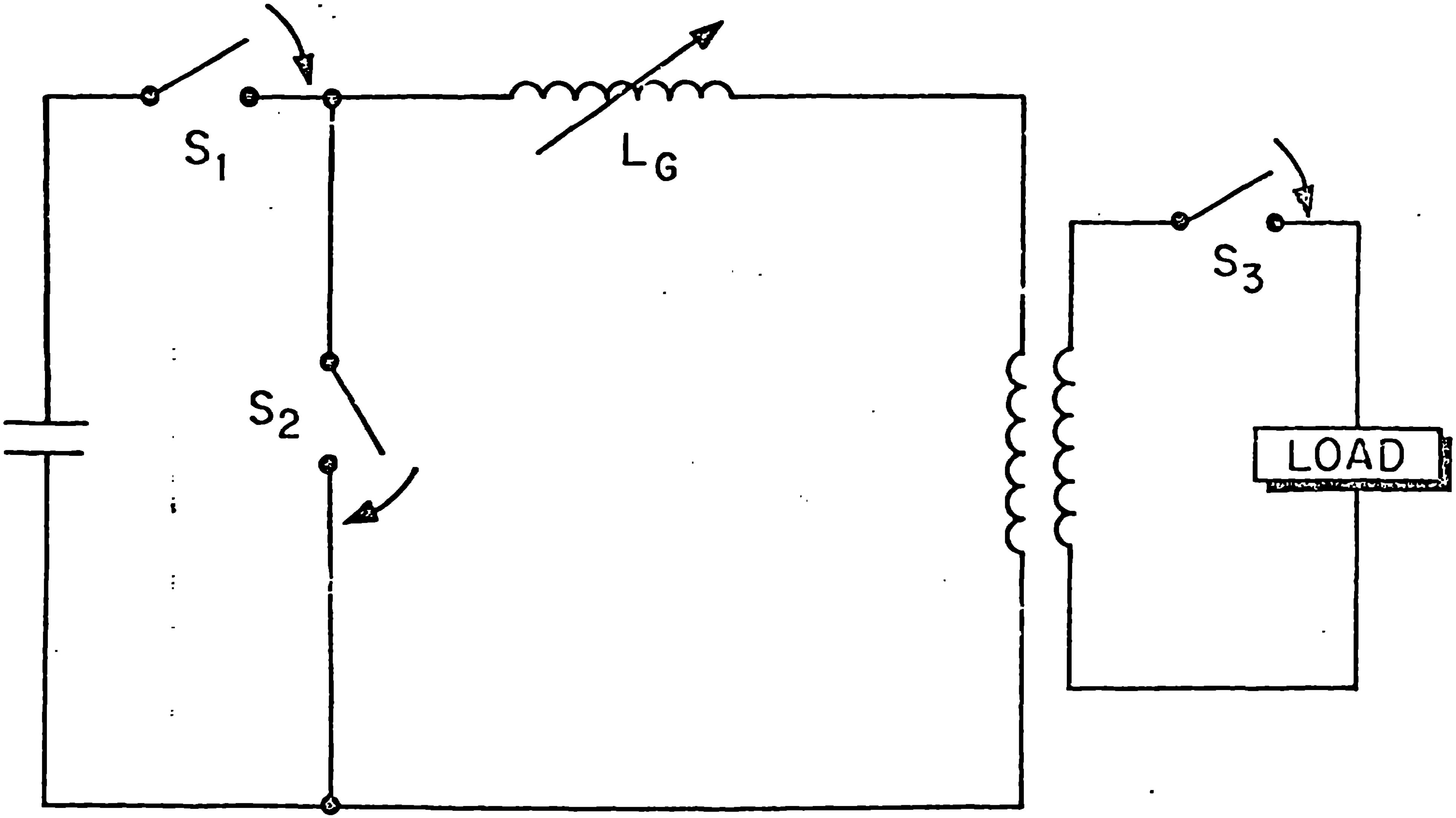
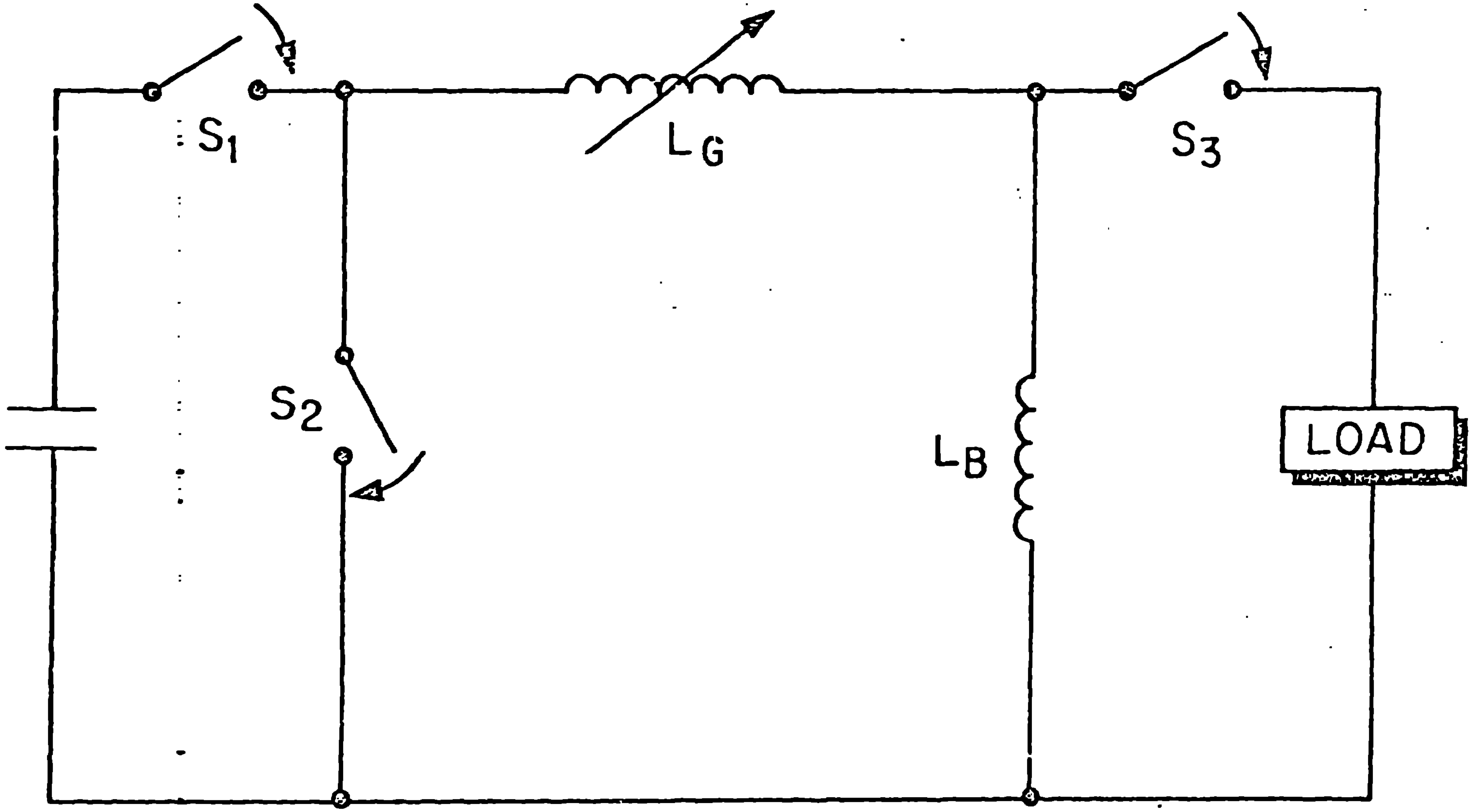


Figure 1.



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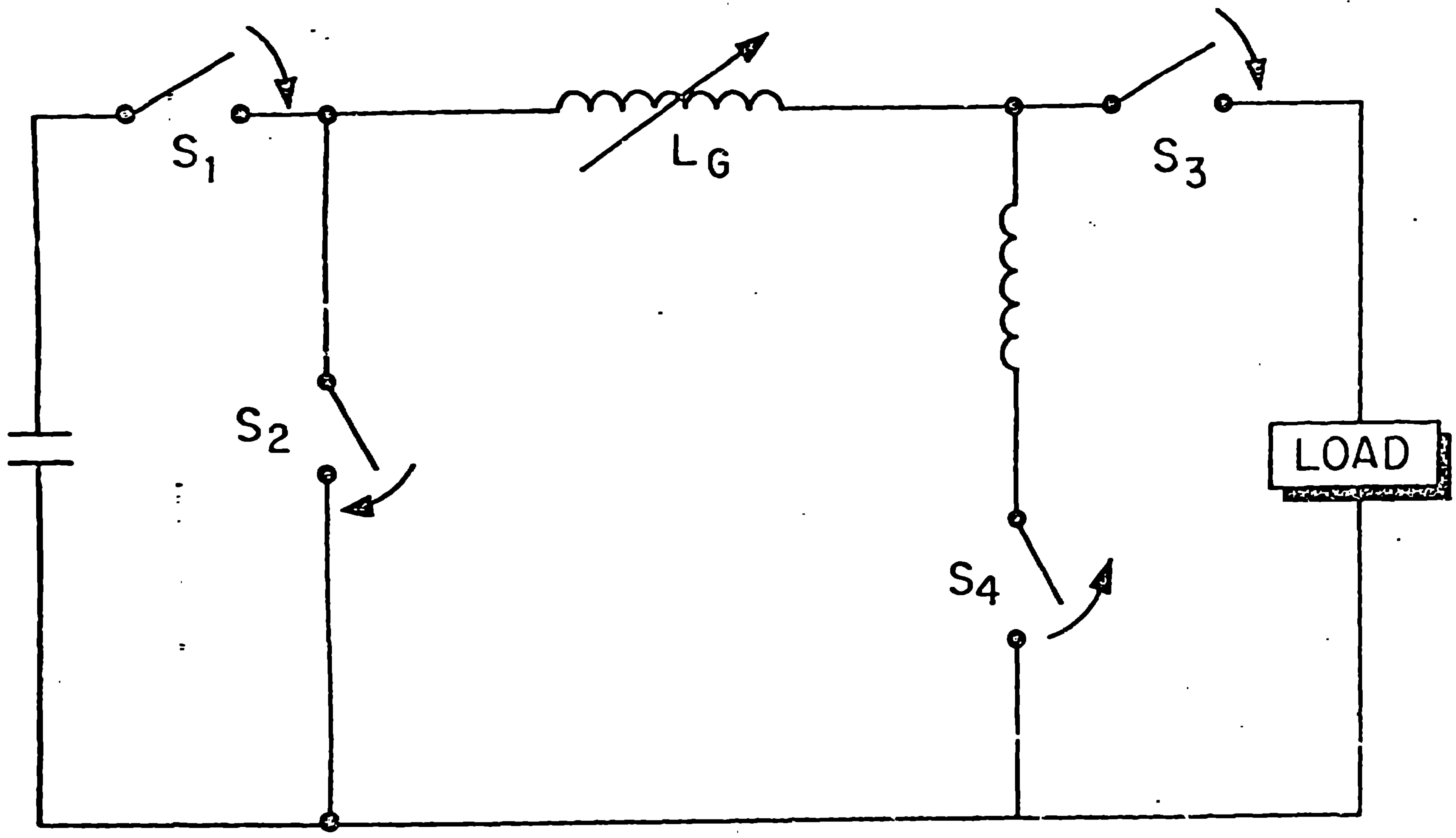

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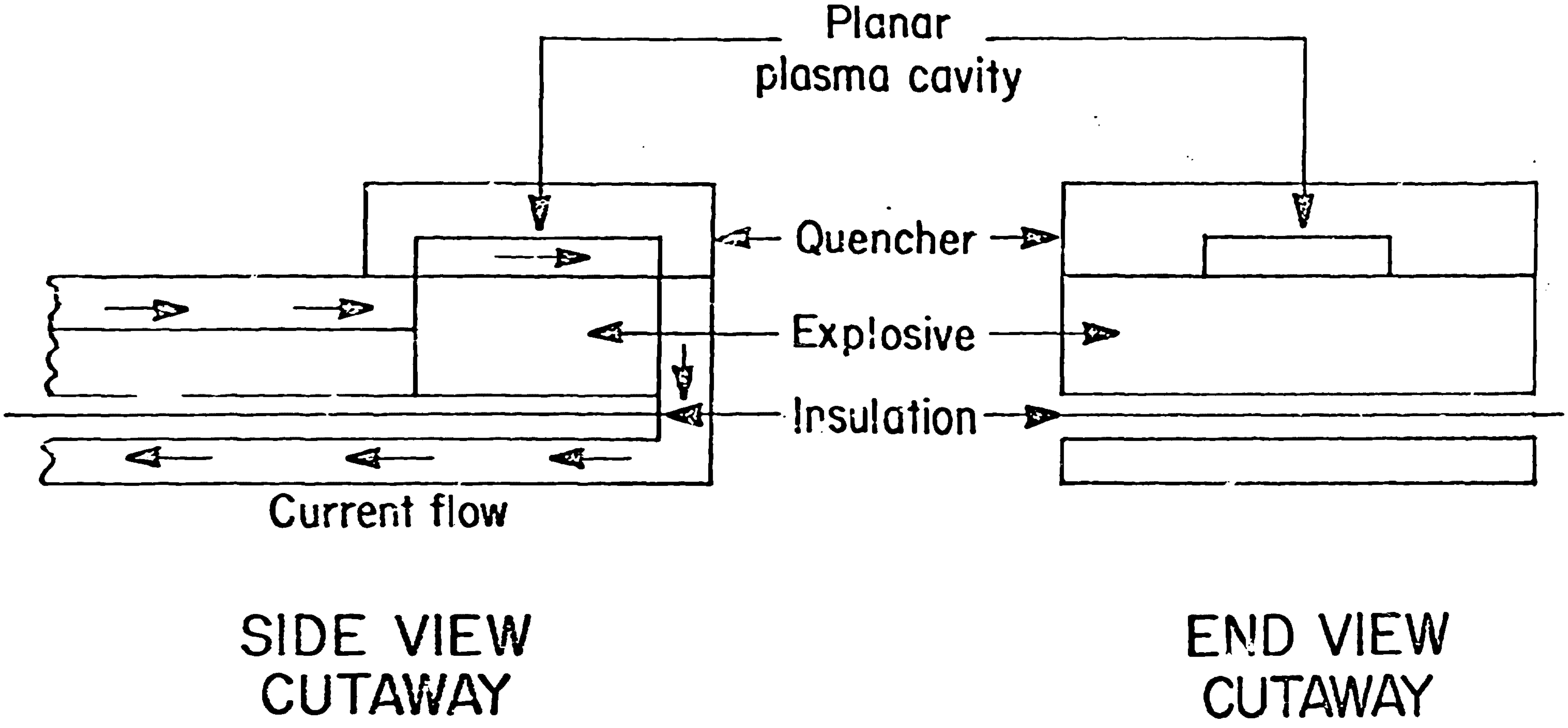

Planar
plasma cavity
Quencher
Explosive
Insulation
Current flow
SIDE VIEW
CUTAWAY
END VIEW
CUTAWAY

Figure 4.

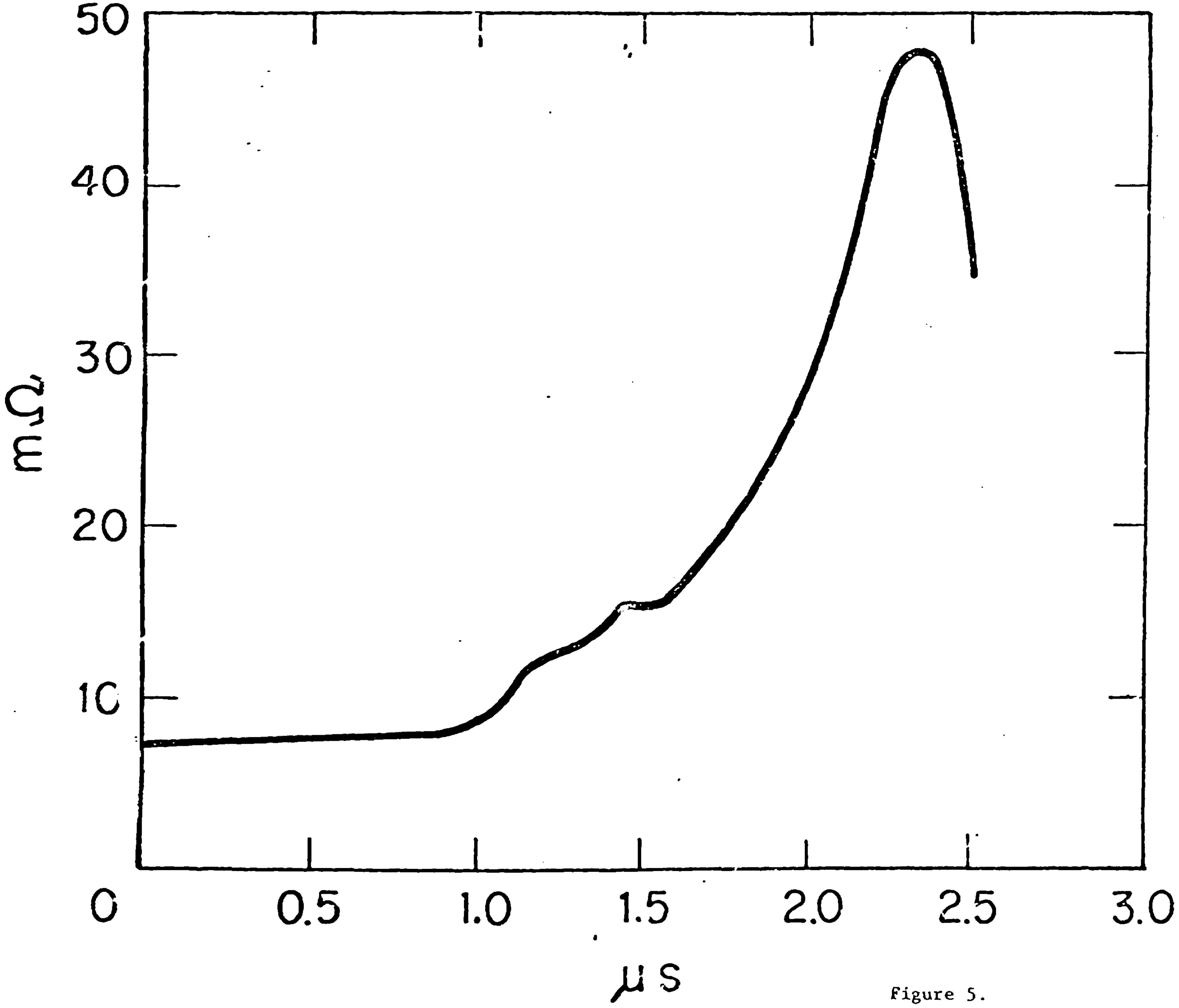


Figure 5.

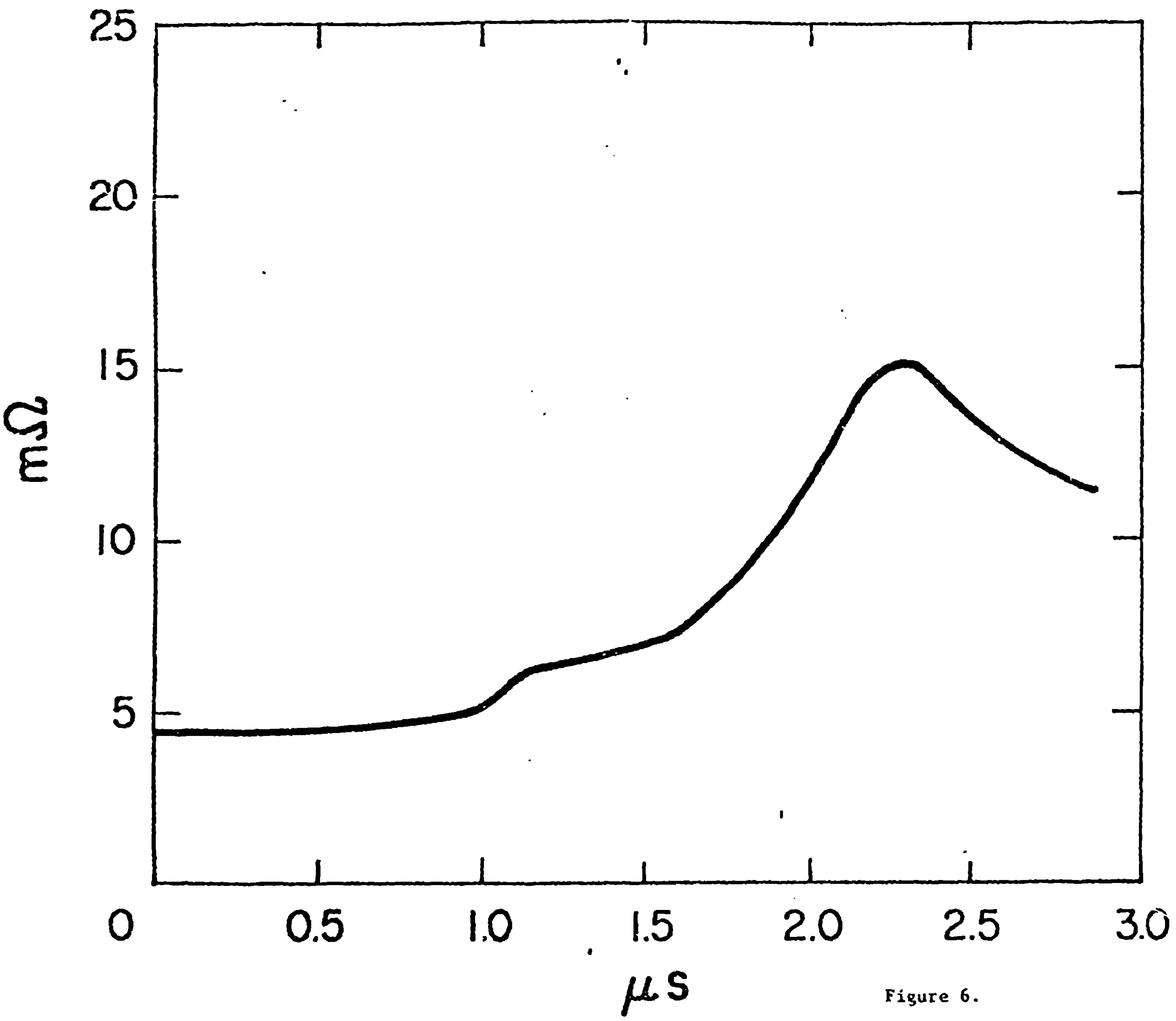


Figure 6.

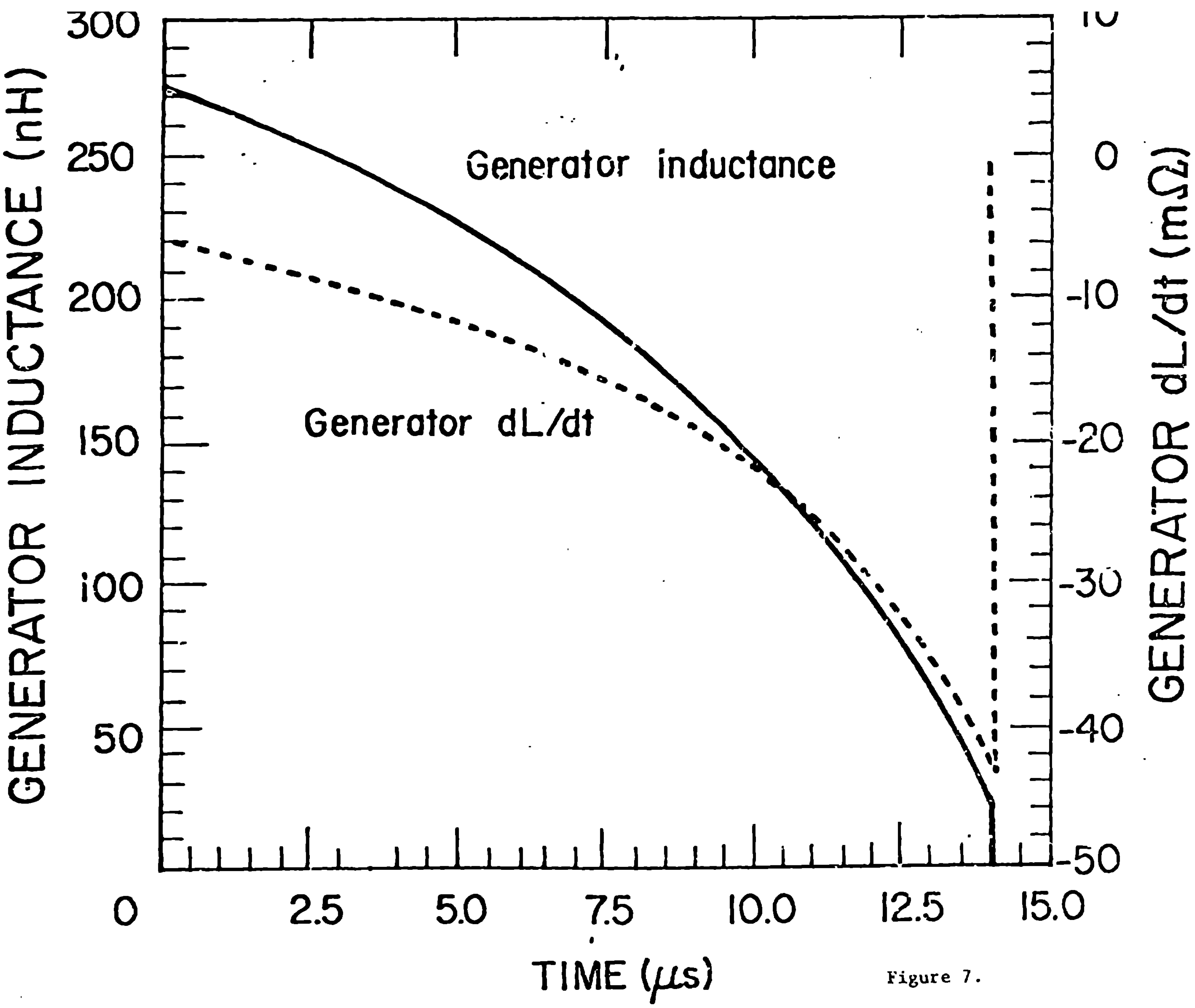

GENERATOR INDUCTANCE (nH)
300
250
200
150
100
50
0
Generator inductance
Generator dL/dt
10
0
-10
-20
-30
-40
-50
GENERATOR dL/dt (mΩ)
2.5
5.0
7.5
10.0
12.5
15.0
TIME (μs)

Figure 7.

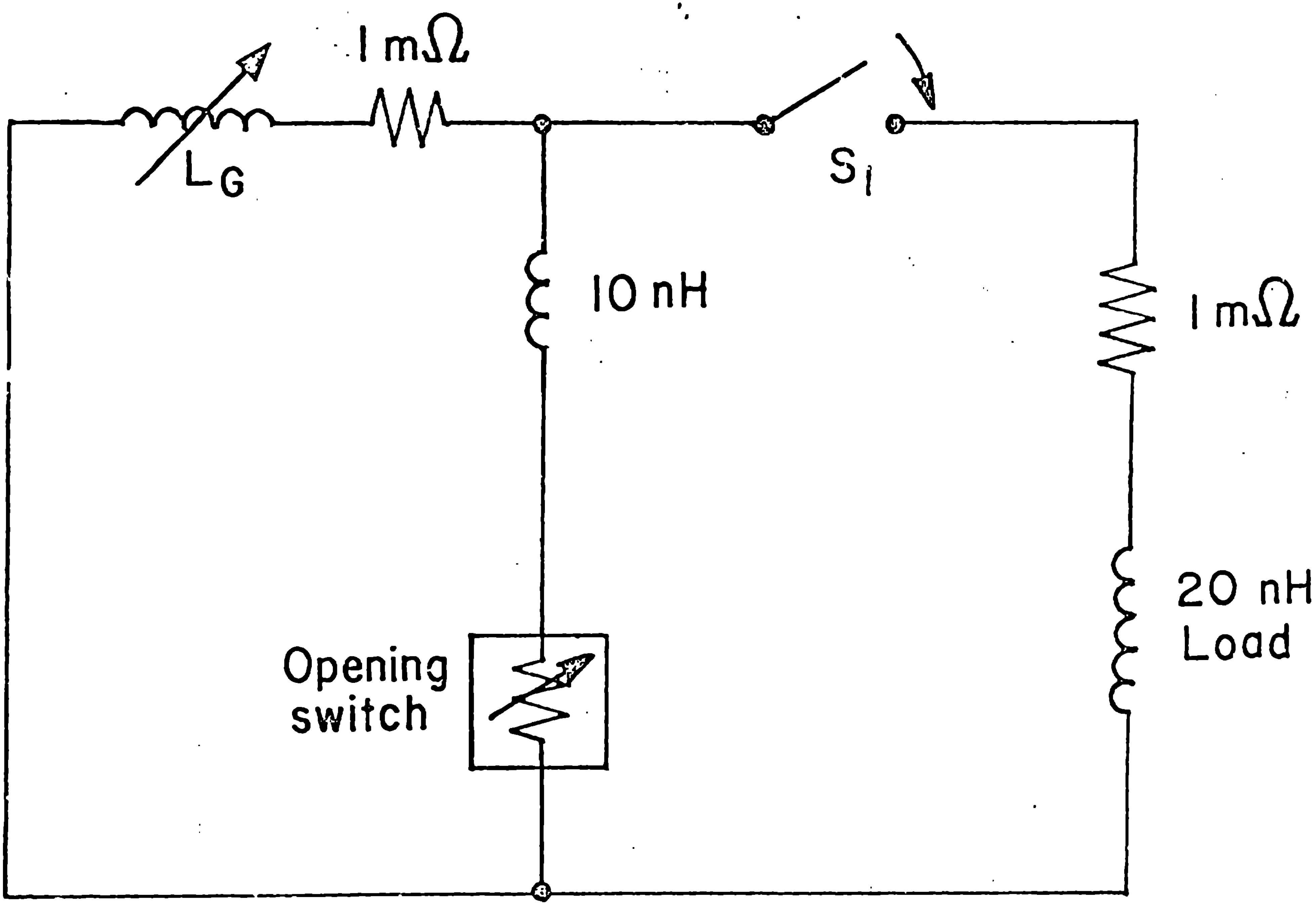


Figure 8.

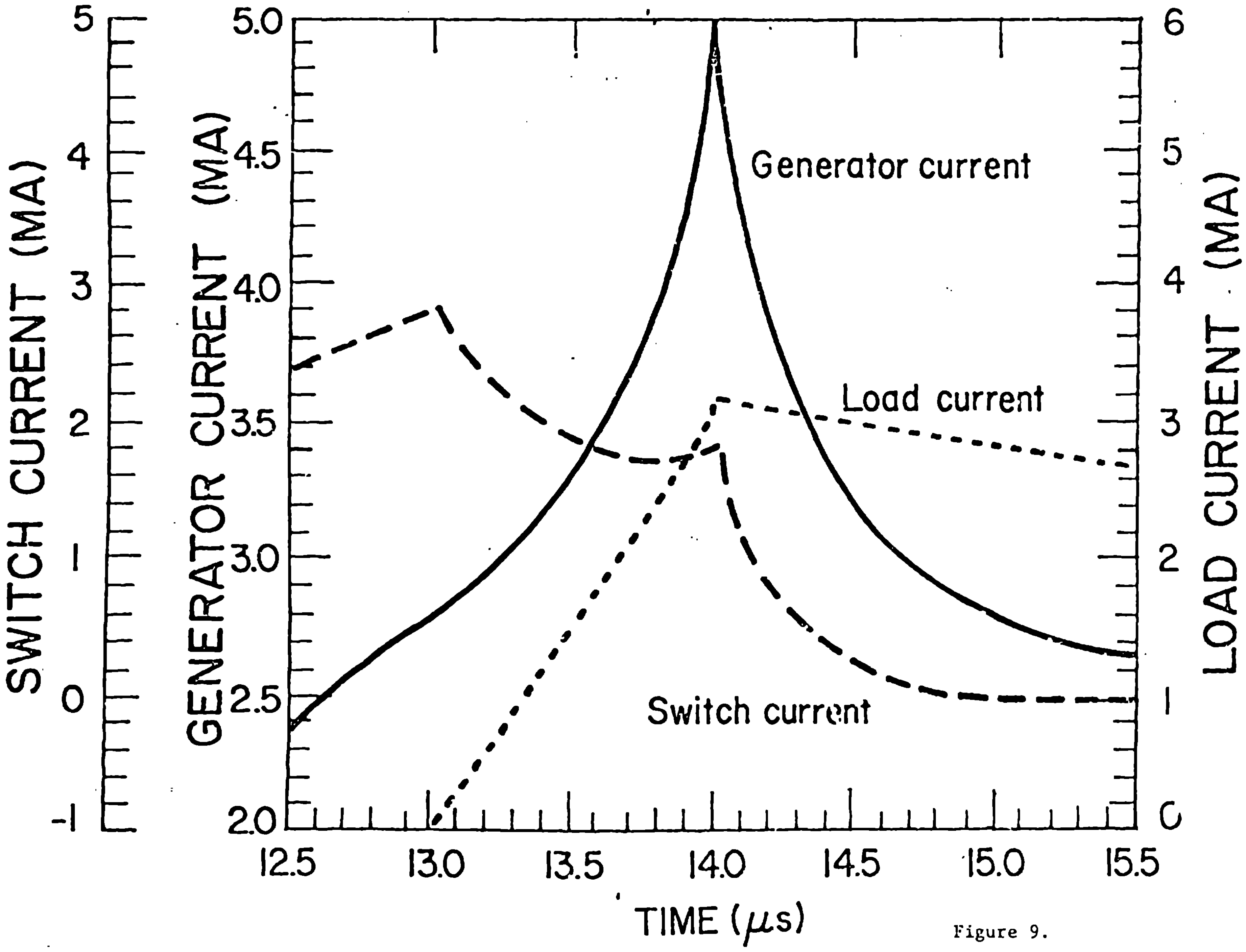

SWITCH CURRENT (MA)
5
4
3
2
1
0
-1
GENERATOR CURRENT (MA)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
LOAD CURRENT (MA)
6
5
4
3
2
1
0
Generator current
Load current
Switch current
12.5
13.0
13.5
14.0
14.5
15.0
15.5
TIME (μs)

Figure 9.

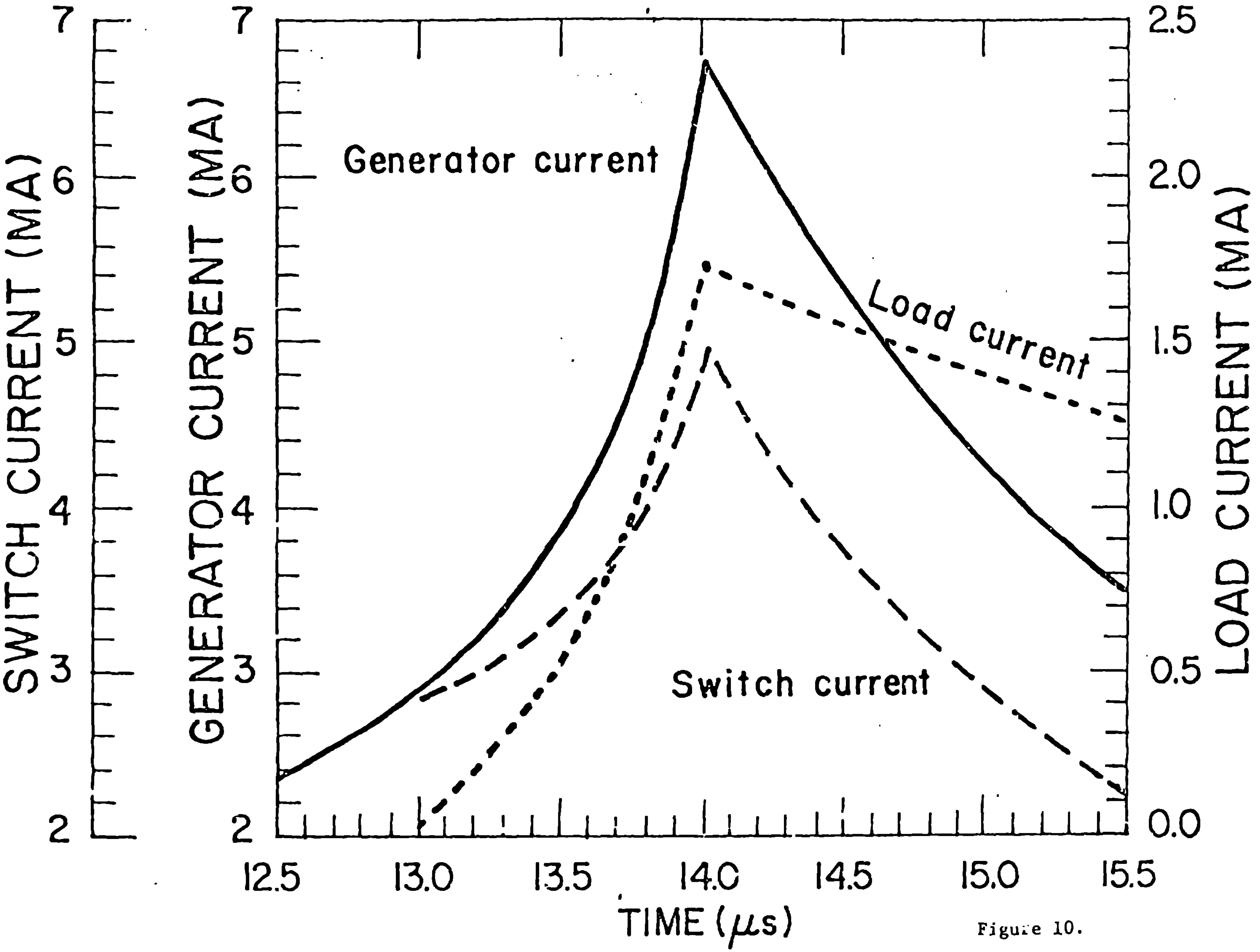
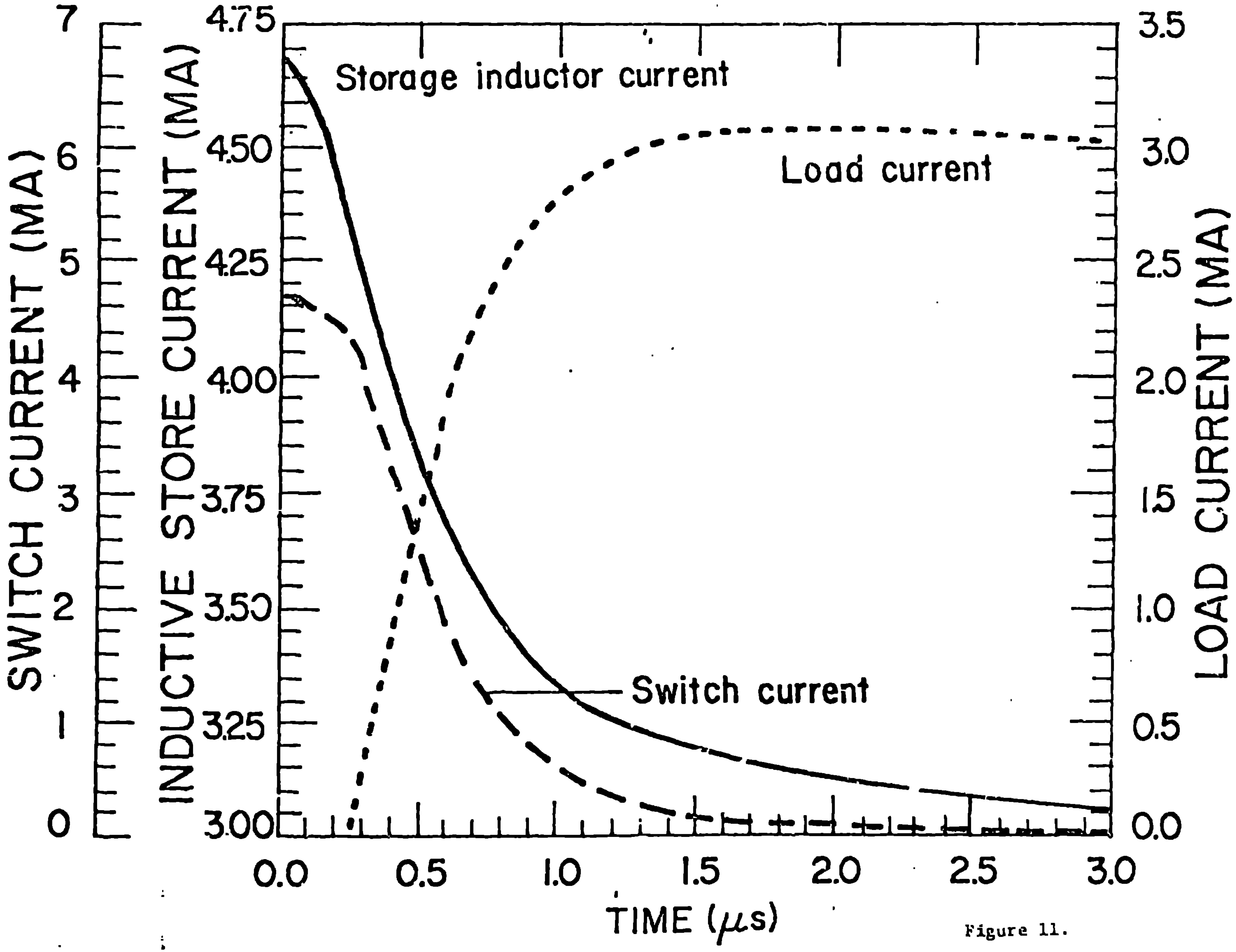

SWITCH CURRENT (MA)
7
6
5
4
3
2
GENERATOR CURRENT (MA)
7
6
5
4
3
2
LOAD CURRENT (MA)
2.5
2.0
1.5
1.0
0.5
0.0
Generator current
Load current
Switch current
12.5
13.0
13.5
14.0
14.5
15.0
15.5
TIME (μs)

Figure 10.



Storage inductor current
Load current
Switch current
SWITCH CURRENT (MA)
0
1
2
3
4
5
6
7
INDUCTIVE STORE CURRENT (MA)
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75
LOAD CURRENT (MA)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
TIME (μs)
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Figure 11.