DETERMINING THE LOSSES IN SPARK GAP SWITCHES*

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Abstract

The variation in losses in gas plasma switches is difficult to measure directly for most practical switches. The approach usually adopted is to measure the voltage across the switch and the current passed through it. The problem area is measuring the voltage, which fast becomes very small compared to the voltage applied to the system as the current through the switch rises. The measurement inevitably loops some magnetic field, and the $\dot{B}$ signal becomes a significant part of the measurement. Other extraneous signals can also interfere with the measurement.

The method described in this paper is a curve fitting method. It relies on the assumption that the loss mechanisms can be closely approximated by a model with a resistance in series with a constant voltage drop, and that the value of these elements is the same for alternating and unidirectional current flows. Excellent fits were in fact obtained which lends credence to the method.

Introduction

The value of switch losses is important both in the design of high power switches and in the design of the circuits they switch. Furthermore, the switch design would be greatly facilitated if the loss mechanisms were known. This knowledge would help by establishing the forces that the enclosure must withstand, and the heat conduction requirements in designing the electrodes.

It has long been thought that switch losses can be represented by a constant voltage drop in series with a resistance. This study assumes that this model is correct and compares the waveforms of two simple circuits with computer simulations of the circuit in which the component values in the model are adjusted to obtain a best rms fit. The resulting fit is excellent in both cases, which indicates that the model is accurate enough for most practical purposes.

One of the circuits, a simple series LR circuit, is used to determine the value of the resistive component of the loss. The other, an underdamped series LCR circuit, is used for the voltage drop component. The former test covered only one gas, Argon, at one pressure and with one set of initial conditions. Two gasses, Argon and an Argon/Oxygen mix, were used in the latter study, and in this case both the gas pressure and voltage were varied. A more extensive study of both circuits would be useful. This is particularly the case for the LR circuit since the resistive losses of switches are particularly important in the high current circuits used in many defense applications.

Test Circuits

The circuit used to determine the switch resistance is a crowbarred series LCR circuit as shown in Fig. 1. The energy in the circuit is initially stored in capacitor C_m, which is a 78 μF, 160 kV Marx generator. The circuit is energized by closing switch S_m, the Marx switches. When the test object is a switch it is triggered by the overvoltage generated by the Marx erection. Closing S_m forms an underdamped resonant circuit with C_m, L_m, R_m, L_1, R_1 and the test object connected in series. This circuit is crowbarred by closing switch S_c as the current reaches its first peak.

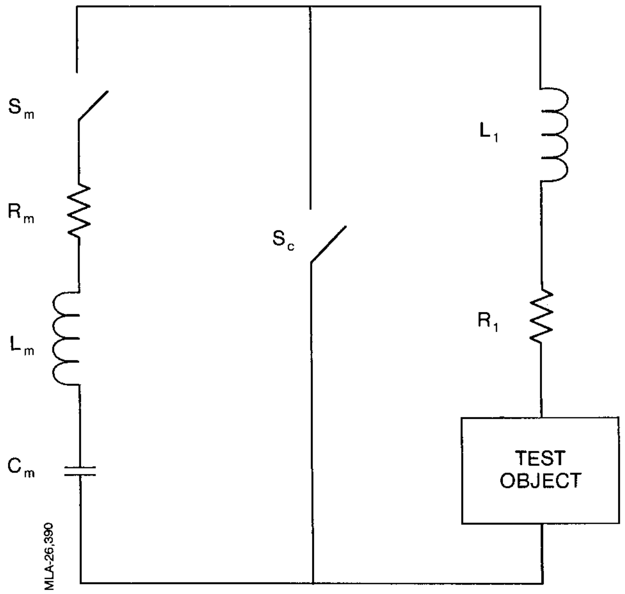

Fig. 1. Schematic of the crowbarred LCR circuit

The waveform after the crowbar closes is the only part of the wave used in the analysis. When the switch closes the test object is connected in series with L_1, R_1 and the crowbar. The coupling between this part of the circuit and the components on the other side of the crowbar is minimal. This active part of the circuit is shown, with a spark gap switch as the test object, in Fig. 2. Here the switch is represented as a battery, V_s, in series with a resistor, R_s.

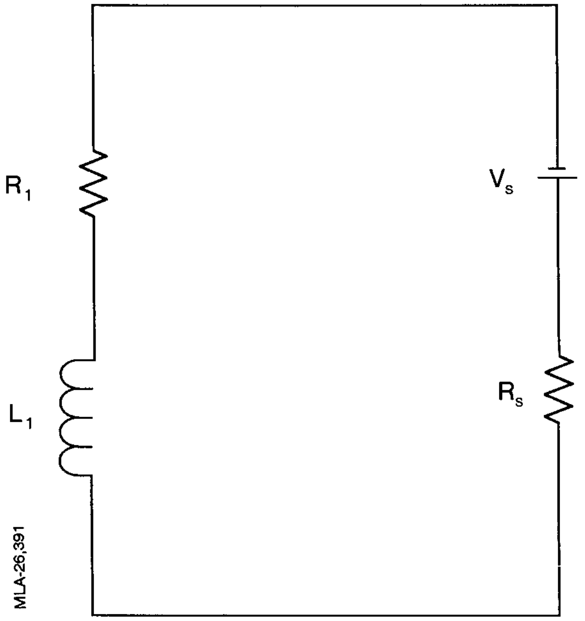

Fig. 2. Part of the Fig. 1 circuit used in the analysis

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14. ABSTRACT

The variation in losses in gas plasma switches is difficult to measure directly for most practical switches. The approach usually adopted is to measure the voltage across the switch and the current passed through it. The problem area is measuring the voltage, which fast becomes very small compared to the voltage applied to the system as the current through the switch rises. The measurement inevitably loops some magnetic field, and the B signal becomes a significant part of the measurement. Other extraneous signals can also interfere with the measurement.

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Two test objects, a spark gap switch and a copper pipe, were inserted in the test object position. The resistance of the copper pipe is negligible, thus the resistance of the switch can be determined if the resistive losses of the circuit can be determined for both configurations.

The key to determining the effective resistance of the test switch is the performance of switch S_c. The characteristics of this switch must be reproducible from shot to shot. The switch used is an explosive switch which behaved as a virtually constant linear element with no measurable shot to shot variation in its impedance.

After switch S_c closes the current in the circuit exponentially decays until the current is zero. When the test object is the switch, the amplitude of the current during the decay is given by the expression:

$$I = \frac{-V_s}{R_1 + R_s} + \frac{I_1 + V_s}{R_1 + R_s} \exp \frac{-t}{\tau} \quad , \qquad (1)$$

where $\tau = L_1/(R_1 + R_s)$, I_1 is the initial current, and the other constants are defined in Figs. 1 and 2. The gap voltage vanishes as the current reaches zero. It should be noted that the exponential decay would continue until it reached a value:

$$I_{min} = \frac{V_s}{R_1 + R_s} \quad , \qquad (2)$$

if the gap voltage maintained its value after current zero. Consequently the slope of the current waveform is discontinuous at current zero.

This circuit is only used to determine the apparent resistance of the gap. It is not useful for determining the apparent reverse voltage because the value of I_{min} is much smaller than the initial current. Consequently small inaccuracies in the positioning of the baseline cause large errors in measurements of this voltage.

The circuit used to determine the reverse voltage characteristic of the gap is shown in Fig. 3. The circuit is underdamped so the circuit modeling the spark gap must be adjusted so that the gap voltage always opposes the current flow. It is therefore modeled with two parallel legs with a battery in series with a diode, elements V_{s1}, D_{s1}, V_{s2} and D_{s2}. The diode is oriented to oppose battery driven current flow. The polarity of the two elements are reversed in the two legs. The switch model is completed with the two series elements switch S_s and R_s.

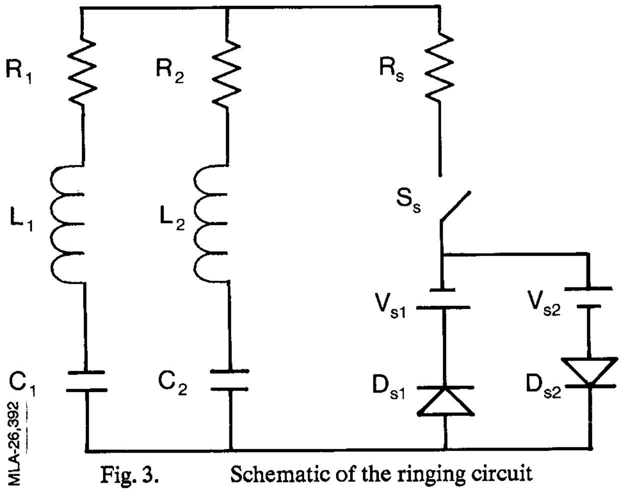


Fig. 3. Schematic of the ringing circuit

The circuit has two parallel capacitor banks in series with two inductors and the resistive losses of these elements, represented by C_1, L_1, R_1, C_2, L_2 and R_2. The two capacitors are initially charged, and the discharge is initiated by closing the test spark gap, S_s.

Diagnostics

In both circuits a current measurement is used in the analysis. In the Fig. 1 circuit it is measured with a Pearson probe connected to a Tektronix 7612 digital oscilloscope by a fiber-optic link. The stored signal is then transferred to the memory of a DEC VAX computer for further processing.

The measurement of the Fig. 3 system current is made with a Rogowski loop. The signal from the loop is hard wired to a Nicolet 4094A digital oscilloscope with FOAMFLEX cable. The signal is transferred via a floppy disc to either an IBM PC or the DEC VAX for processing. Both the raw signal and integrated signals are used in the analysis.

Analysis of Crowbarred Data

The Fig. 1 system was only available for these tests for a short time, and much of this time was spent in arranging and adjusting the instrumentation. Consequently only a total of nine test shots were fired, and the instrumentation failed to generate data on one of these shots. The switch was in the circuit for three shots. The other shots, including the uninstrumented shot, were fired with a copper pipe in place of the gap. The pipe was approximately the same diameter as the switch electrodes, so the characteristics of the circuit were not changed significantly between the two configurations.

The same switch conditions, gas type and pressure, were used for all the switch shots. Initially three shots were fired with the copper pipe in place. One of these was the uninstrumented shot. These shots were followed by three shots with the switch replacing the copper pipe. Then three more copper pipe shots completed the series. This shot series was adopted so that changes in the circuit parameters, if present, would show up. However, no change was observed.

As a further check on the constancy of the circuit the resistance of the crowbarred loop was measured with a digital multimeter before each shot. After the series had been completed the circuit was fired with a shorted and an open crowbar switch to obtain ringout characteristics under both conditions. These data are used to calculate the inductance for both configurations, and thus obtain the inductance of the crowbarred section by subtraction.

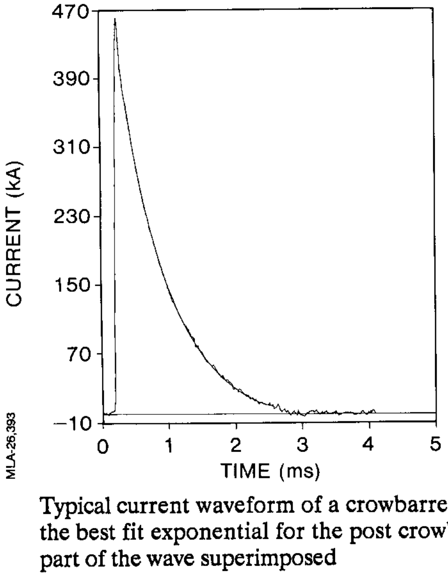


Fig. 4. Typical current waveform of a crowbarred shot with the best fit exponential for the post crowbar closure part of the wave superimposed

The best fit waveform, based on the Eq. 1 formula, is found for each of the five instrumented shots. Fig. 4 is the current waveform of a typical switch shot with the best fit exponential superimposed on it. The variables in the exponential fitting routine are I_i, I_{min} and τ. The value of τ and crowbarred inductance are used to calculate the value of the series resistance, $R_1 + R_2$, in the circuit. This value can be used to calculate the value of the effective gap voltage. However, as mentioned earlier, this value is not accurate because substantial errors are introduced by baseline shift.

Table 1 gives the values of the variables giving the best fit exponential, the dc resistance across the crowbar before each shot and the circuit resistance and apparent gap voltage obtained from these data. All the resistance figures covering the same circuit configuration are closely bunched. Table 2, which gives the mean values and standard deviation for each set, shows this feature. The figures in the best fit baseline column of Fig. 1 give the voltage towards which the best fit exponential is decaying. This figure would give the voltage drop of the switch if the measurement baseline were in the correct location.

TABLE 1
TEST DATA AND CALCULATIONS FROM THE CROWBARRED SYSTEM

TEST OBJECT	PEAK CURRENT (kA)	BEST FIT BASELINE (kA)	TIME CONSTANT (μs)	DC RESISTANCE (mΩ)	COMPUTED RESISTANCE (mΩ)	BASELINE VOLTAGE (V)
Short	468	1.06	791	2.89	4.05	4.28
Short	466	1.21	797	2.91	4.02	4.88
Switch	465	-10.97	724	2.92	4.42	-48.50
Switch	461	-13.65	736	2.81	4.41	-60.20
Switch	479	-8.75	735	2.87	4.35	-38.00
Short	450	-1.27	781	3.04	4.10	-5.22
Short	448	-2.46	784	2.94	4.08	-10.02
Short	473	-1.04	788	2.82	4.06	-4.22

TABLE 2
MEAN VALUES AND STANDARD DEVIATIONS
OF THE RESISTANCE AND VOLTAGE DATA IN TABLE 1

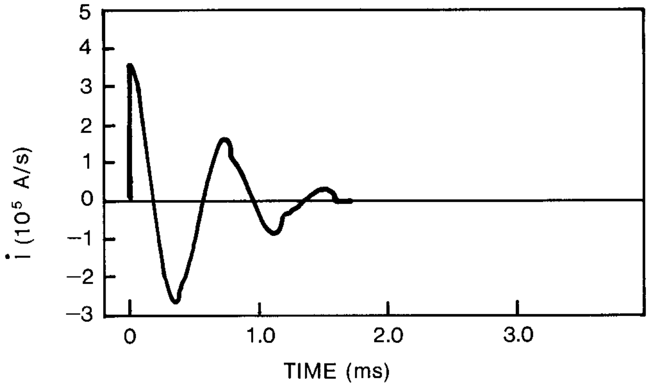
DATA COVERED	MEASUREMENT	STANDARD NUMBER OF SHOTS	MEAN VALUE	DEVIATION (% OF MEAN)
All	dc resistance	8	2.90 mΩ	2.51
Switch shots	Resistance	3	4.39 mΩ	0.86
	Voltage	3	-48.90 V	22.70
Short shots	Resistance	5	4.06 mΩ	0.75
	Voltage	5	-2.10 V	310.00

The resistance in the gap is given fairly accurately by the difference between the resistance with the switch connected and the resistance with the short. This gives a figure of 330 μΩ. The possible error in this figure is relatively high, despite the small standard deviation of the data, because the data base is so small. The variation in the values of the baseline voltage are too large to estimate the value of the constant reverse voltage of the gap using this method.

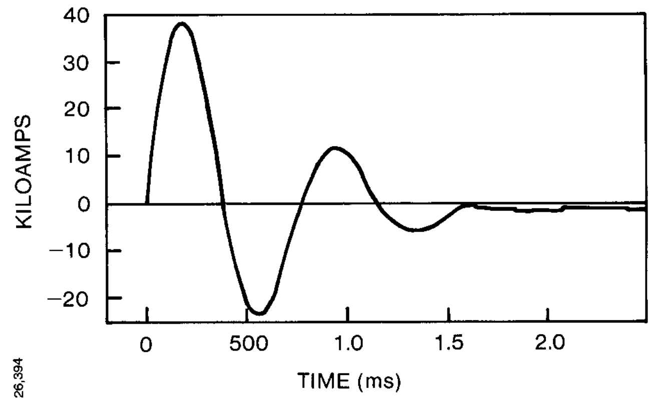
Analysis of Oscillatory Data

The circuit used to calculate the voltage drop across a spark gap switch has two identical, parallel circuits each with a 3 mF capacitor bank feeding an inductor through six low impedance coaxial cables. The output terminal of each inductor is connected to the test gap by low impedance coaxial cables. the other terminal of the test gap is connected to the capacitor ground side terminal through the braids of the low impedance cables.

Fig. 5 shows the signal from the Rogowski loop on one of the capacitor legs, and a digitally integrated version of this signal. A discontinuity in the slope of both waveforms can be seen as the current passes through zero. The step in the raw, $\dot{I}$, signal suggests that the losses in the gap have a constant inverse voltage component. Consequently an underdamped LCR series circuit is used to determine the constant voltage drop in a spark gap switch.



(a) $\dot{I}$ SIGNAL



(b) INTEGRATED $\dot{I}$ SIGNAL

Fig. 5. Typical $\dot{I}$ and integrated $\dot{I}$ signal from the Rogowski probe on one of the oscillatory test shots

The circuit used in the analysis is shown in Fig. 3. This circuit behaves linearly between current zeros. The initial peak in the current waveform is given by the expression:

$$I = (V_c - V_s)\sqrt{L/C} \exp \frac{-d \times \cos^{-1} d}{\sqrt{1 - d^2}} , \tag{3}$$

where,

$$V_s = |V_{s1}| = |V_{s2}| , \qquad d = R\frac{\sqrt{C/L}}{2} ,$$

$$R = \frac{R_1 \times R_2}{R_1 + R_2} , \qquad L = \frac{L_1 \times L_2}{L_1 + L_2} , \qquad C = C_1 + C_2 .$$

The voltage on the circuit the instant before the current reverses is:

$$V\,(t = \pi/\omega - \delta) = D\,(V_c - V_s) , \tag{4}$$

where ω is the resonant frequency in radians per second and $D = \exp(-\pi \times R/2/\omega/L)$, the half cyclic current, or voltage, reversal if V_s were not in the circuit.

The voltage on the circuit the instant after the current is:

$$V\ (t = \pi/\omega + \delta) = V\ (t = \pi/\omega - \delta) - 2 \times V_s \quad . \qquad (5)$$

This is the drive voltage on the next half cycle, and it can be used to determine the next current minimum. This procedure can be used to calculate the amplitude of the succeeding current maxima and minima.

The values of D and V_s, and the position of the baseline, which provide the best fit of the maxima and minima to the current waveforms in the test circuit, are found iteratively. The capacitance in the test circuit, and the period are known and are used to determine the inductance in the circuit. The initial peak in the current is computed using these data, and this value is compared with the measured value, adjusted for the baseline shift, to check the analysis.

Tables 3, 4 and 5 give the results of the analysis. Both Tables 3 and 4 are for the same Argon/Oxygen gas mix. The resistive losses in the circuit were reduced for the latter table. The data in Table 4 suggests that the voltage drop in the gap increases as the peak current increases. However, the results in Table 4 are not born out in Table 3 which analyses eight shots, all at the same level. In this set the gap voltage figures range from lower than the lowest value, at the lowest capacitor charge voltage level, in Table 4, to slightly above the mean value at the highest charge voltage.

Table 5, which is for Argon, shows no indication of an increasing gap voltage as the circuit current is increased. However, there is a large variation in the gap voltage during the series. The main statistically significant difference between the Argon and Argon/Oxygen data is that the gap voltage drop is higher for the latter. The resistance figures in Tables 4 and 5 are not significantly different, so the resistance is little influenced by the gas type. One explanation of this could be that a major part of this loss is the spreading resistance loss in the electrode. If this is so it will be frequency sensitive due to skin effect.

TABLE 3
ANALYSIS OF RINGOUT DATA FOR AN 80% ARGON, 20% OXYGEN DIELECTRIC GAS MIX WITH SIX CABLES PER CAPACITOR BANK

CHARGE VOLTAGE (kV)	MEASURED PEAK CURRENT I(MEAS) (kA)	PRESSURE (psig)	CIRCUIT RESISTANCE (mΩ)	GAP VOLTAGE DROP (V)	COMPUTED PEAK CURRENT I(COMP) (kA)	I(MEAS)/ I(COMP)
3	118.1	10	5.07	96	117.5	1.005
4	160.9	10	5.11	115	157.0	1.025
4	161.2	10	5.03	98	158.1	1.020
4	161.5	20	5.36	95	156.6	1.031
4	161.5	20	5.34	95	156.7	1.031
4	161.5	10	5.31	75	157.6	1.025
4	161.4	10	5.00	109	157.9	1.022
4	162.0	20	5.63	74	156.0	1.038
4	161.1	20	4.90	125	157.7	1.022

TABLE 4
ANALYSIS OF RINGOUT DATA FOR AN 80% ARGON, 20% OXYGEN DIELECTRIC GAS MIX WITH TWELVE CABLES PER CAPACITOR BANK

CHARGE VOLTAGE (kV)	MEASURED PEAK CURRENT I(MEAS) (kA)	PRESSURE (psig)	CIRCUIT RESISTANCE (mΩ)	GAP VOLTAGE DROP (V)	COMPUTED PEAK CURRENT I(COMP) (kA)	I(MEAS)/ I(COMP) NO. VALUE
2	77.6	10	4.93	81	78.0	0.995
2	77.8	10	4.46	85	79.1	0.984
2	78.0	10	4.26	97	79.1	0.986
2	78.3	20	4.59	90	78.6	0.996
2	78.1	20	4.12	98	79.5	0.982
2	78.1	20	4.53	85	78.9	0.990
3	118.8	10	4.30	109	119.8	0.992
3	116.2	10	4.17	113	120.4	0.965
3	123.2	10	4.22	112	121.5	1.014
3	117.2	20	4.42	103	119.8	0.978
3	121.1	20	4.22	113	123.9	0.977
4	160.4	20	4.39	120	160.6	0.999
4	160.0	20	4.26	130	160.9	0.994
4	159.9	20	4.40	120	160.0	0.999
4	159.3	10	4.24	132	160.9	0.990
4	160.5	10	4.51	106	160.6	0.999
4	159.2	10	4.24	135	160.8	0.990

TABLE 5
ANALYSIS OF RINGOUT DATA FOR ARGON DIELECTRIC GAS

CHARGE VOLTAGE (kV)	MEASURED PEAK CURRENT I(MEAS) (kA)	PRESSURE (psig)	CIRCUIT RESISTANCE (mΩ)	GAP VOLTAGE DROP (V)	COMPUTED PEAK CURRENT I(COMP) (kA)	I(MEAS)/ I(COMP)
2	77.9	10	4.44	63	80.1	0.973
2	77.4	10	4.42	61	80.2	0.965
2	77.7	20	4.37	64	80.2	0.969
2	77.8	20	4.60	52	80.1	0.971
2	77.7	20	4.31	65	80.3	0.968
3	119.5	10	4.60	48	121.4	0.984
3	119.0	10	4.51	63	121.1	0.983
3	118.8	20	4.46	63	121.3	0.979
3	118.6	20	4.51	67	120.9	0.981
3	119.3	20	4.59	59	120.9	0.987
4	161.7	10	4.62	59	161.9	0.999
4	161.7	10	4.55	59	162.3	0.996
4	161.3	10	4.51	70	162.0	0.996
4	161.4	20	4.53	65	162.1	0.996
4	161.6	20	4.48	71	162.2	0.996
4	161.5	20	4.46	76	161.6	0.999

Conclusion

The losses in a spark gap can be viewed as consisting of a constant resistance in series with a constant voltage drop. The resistance in the test gap with Argon dielectric is ~300 μΩ, and this loss mechanism did not appear to be sensitive to changes in the gas type. The voltage drop through a gap seems to vary significantly from shot to shot. It varies around a mean value of ~110 V with an 80 percent Argon, 20 percent Oxygen gas mix, and ~60 V with Argon gas.