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Spark Energy Measurements Using Oscilloscopic Methods

INTRODUCTION

The voltage-current method of determination of spark energy is satisfactory and informative. Readings may be taken in a minimum amount of time (after the initial system set up) and give the total electrical energy in the arc stream. It is of no significance whether this energy is later transformed to light, heat or sound because the actual causes of ignition are not confined to any one of these forms. The total useful energy is measured in its most basic form. Energy dissipated as heat in the plug shell, center conductor and semi-conductors, if present, is not measured by this method. This means that non-contributing energy is eliminated from the results.

SUMMARY

This method consists of the observation of the time variation of both the arc stream current and voltage and the point by point multiplication of these two curves to obtain a power vs. time curve for the arc. The integral of this curve is the total arc stream energy.

The oscilloscopic method gives a complete instantaneous picture of what occurs in the arc. It shows spark to spark variations which may exist and allows, using simultaneous measurements, exact calculations of the energy in any given spark. This allows some correlation between the ignition process and spark energy distribution which should be more fully investigated.

The ability of the method to measure only that energy which is useful and to measure that energy before losses occur makes it accurate.

The appendix shows a typical problem in energy measurement and the process used in its solution.

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DISCUSSION OF METHODS:

In the measurement of spark energy, the question arises as to whether one wishes to interest himself in the average energy per spark or the instantaneous energy per spark. In measuring average energy, a device which totals up the energy from several sparks may be used. This total energy may be divided by the number of sparks used and a figure for average spark energy obtained. A figure of average spark energy does not, however, tell the ignition story. It is known that the time of discharge (for a given energy) does have an effect on the ignition process. This means that a better correlation can be obtained between spark energy and ignition when the distribution of this energy is known. The only satisfactory way to obtain the time distribution of energy is to use an oscilloscopic method and measure the electrical power in the spark as a function of time. The electrical power in the spark at a given time is the product of the discharge current and the arc voltage at that instant. For a satisfactory picture of the spark energy, it is necessary to measure the discharge current and the arc stream voltage as functions of time.

A direct, but undisturbing, method of measuring the current in the discharge circuit is to use a differentiating network to read the derivative of the tank voltage. This inserts no resistance in the discharge network and so does not absorb any energy from the tank capacitor. However, a resistor is required which has a relatively high value of resistance which permits the use of carbon or some such substance to obtain the necessary large values of R/L . (See next section).

In the case of the use of more than one capacitor in the discharge circuit (which may be separated by impedance), the system is still valid by differentiating the voltage across each capacitor and adding them instantaneously.

When measuring currents on systems where it is impossible to make a connection to the tank capacitor terminal, a method other than the differentiating circuit must be used.

The recommended method for measuring discharge currents when the test exciter is completely sealed is the use of a specially designed and constructed current transformer. This current transformer must meet the requirements for ratio and phase shift as set forth in the section on the analysis of the current transformer (see page 24). The use of a current transformer allows the effective inserted impedance in the circuit to be reduced by the square of the transformer ratio from the actual values used. Since this is possible it allows the constructions of resistors having a better R/L ratio because the actual resistance may be considerably higher than that which is effective in the circuit.

A viewing resistor may be used if developments are such that resistors having the proper values of R/L and suitably low values of resistance can be obtained.

Another method of viewing the current in the discharge circuit of a sealed exciter is to measure the flux at a given distance from the conductor carrying the discharge current. This flux is directly proportional to the current in the conductor and can be measured by using such devices as magnetoresistors or Hall generators.

Another method has been used, but is a poor method and is mentioned only as a warning against it. This is to place the oscilloscope leads across a portion of the shielding on the discharge cable. This method gives varying results depending on the type of cable used, is extremely difficult to calibrate and does not have an inductance which is low enough to be useful.

When measurements are required on breadboard systems, or systems where a tank capacitor terminal is available, or can be made available, the accuracy and convenience of the differentiator are desirable. The differentiator method of measuring current allows also the simultaneous reading of voltage and current on a dual beam oscilloscope, or through the use of an electronic switch having a suitably high switching rate. This may be accomplished because the small voltage drops encountered in placing the differentiator ground connection at the tip of the plug have no appreciable effect on the current flowing through the resistance of the differentiating circuit. Heretofore, the reading of voltage and current simultaneously on the same oscilloscope was impossible because the ground of the viewing resistor could not be placed at the extreme tip of the plug and consequently erroneous readings would have been obtained. The current-transformer method may also be used to obtain simultaneous readings of voltage and current because of the existence of magnetic coupling only between primary and secondary windings.

The method of spark energy determination by a voltage-current method, while it entails some valuable equipment, can be set up so that the process becomes one of simple operation. The process of evaluation of energy from the oscilloscopic patterns could very conceivably be done by clerical employees. All auxiliary equipment needed for measuring discharge current and arc voltage for either surface gap systems or air gap systems can be made extremely simple in operation.

ERRORS IN USING VIEWING RESISTORS:

Consider the method of current measurement using an inserted viewing resistor. This resistor, of course, must be inserted in series with the discharge path, normally in the ground side of the line to prevent high voltage damage to measuring equipment.

Two primary considerations must be observed in selecting this resistor:

- a. The resistor must have an extremely low inductance so the waveforms of voltage observed across it will represent the currents that flow through it multiplied by the value of the resistance and not inductive drop.
- b. The resistance should have a value which is low enough so as not to effect the transfer of energy from the tank to the plug. A negligible amount of energy should be absorbed in the resistor.

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It would be well to examine the circuits and find out what values of resistance and inductance could be tolerated under various conditions. These values as derived in the following discussion, are as follows:

12 JOULE SYSTEM

Type	Tank (mfd)	Viewing Resistor	
		R (ohms)	L (Hys)
Surface	5.28	.00058	93.7 x 10 ⁻¹²

2 JOULE SYSTEM

High Tension	1.0	.00651	3720 x 10 ⁻¹²
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The foregoing values of R and L, to be combined in a single element, become extremely difficult to obtain. Various tricks, such as flux cancellation, can be used to reduce the residual inductance, but a satisfactory solution meeting the calculated requirements is not now available. Another problem which arises with the use of resistors is the change that may occur in the resistor when it is heated by the current flowing in it. This, of course becomes more pronounced as the resistance value rises above the limits set here.

In order to calculate the values which can be tolerated in viewing resistors, it is necessary to establish the limits of energy which can be absorbed in this resistor and the amount of voltage across the inductance inherent in this resistor.

Since it is necessary and desirable to maintain as much accuracy as possible, the energy loss will be held to two per cent of the output energy. The inductive voltage drop which will be assumed tolerable is a value equal to ten per cent of the peak viewing resistor voltage. This figure is allowed to be large because the inductive component voltage drop becomes maximum when the resistive voltage drop is zero and diminishes from this peak value when the resistive voltage drop increases to its maximum.

The discharge system used for the basic calculations are:

- (1) A surface gap system having a tank capacitor of 5.28 mfd and a stored energy of 12 joules and
- (2) A high tension triggered system having a tank capacitor of 1 mfd and a stored energy of 2 joules.

Certain assumptions were necessary to somewhat simplify the calculations. All current waveforms were assumed to be sinusoidal allowing the use of rms values in calculating power loss and allowing the maximum slope to be determined without undo mathematics. The waveforms used were obtained by use of a differentiating circuit allowing the discharge current to be undisturbed by inserted resistors.

In the case of the surface system, the current waveform appeared as Fig. 1:

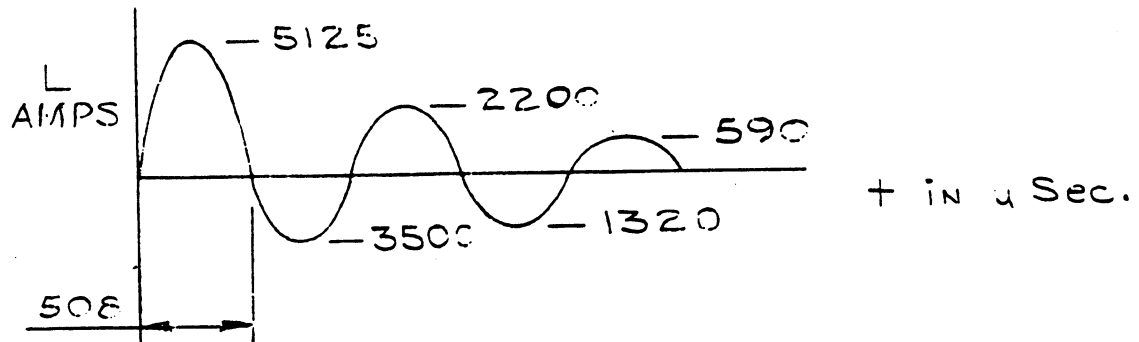


FIGURE 1.

Calculating the energy loss on the basis that

$$U_p = I^2 R t_p \text{ joules}$$

where U_p is energy loss per half cycle sine wave current pulse having an effective value I of duration t_p in resistor R

Pulse	I	I^2
1	3620	13×10^6
2	2470	6.1×10^6
3	1550	2.4×10^6
4	935	$.87 \times 10^6$
5	417	$.17 \times 10^6$

$$U_t = \sum I^2 R t_p$$

where U_t is the total energy absorbed for all pulses.

Solving for R , which is the unknown.

$$R = U_t / \sum I^2 t_p$$

$$\sum I^2 t_p = (22.54 \times 10^6) (5.08 \times 10^{-6})$$

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$$\sum I^2 t_p = 114.5 \text{ amp}^2 \text{sec}$$

It now becomes necessary to determine the allowable energy in the resistor. Since the output energy has been calculated elsewhere as 3.34 joules, the allowable loss based on 2 per cent of output is

$$U_t = (.02)(3.34) = .0668 \text{ joules}$$

The resistor value then may be calculated as

$$R = .0668/114.5 = .00058 \text{ ohms}$$

The dissipation of this resistor is within the specified limits. If this resistance is inserted in the discharge path, the peak voltage appearing across it will be

$$e_{\text{peak}} = i_{\text{peak}} R = 5128 \text{ amps} \times .00058 \text{ ohms} = 2.98 \text{ volts}$$

If the 10 per cent limit is used, the maximum voltage which may be seen across the inductance must be limited to

$$e_L \text{ peak} = (.10) \times 2.98 = .298 \text{ volts}$$

and since

$$e_L = L di/dt$$

then the allowable inductance will be found from

$$L = e_L(\text{peak}) / |di/dt|_{\text{max.}}$$

for pulse number 1

$$i = 5128 \sin \frac{2 \pi t}{10.16 \times 10^{-6}}$$

and

$$|di/dt| = \frac{5128 (2 \pi)}{10.16 \times 10^{-6}} \cos \frac{2 \pi t}{10.16 \times 10^{-6}}$$

$$di/dt_{\text{max}} = \frac{5128 (2 \pi)}{10.16 \times 10^{-6}} = 3.18 \times 10^9 \text{ amps/sec}$$

The maximum allowable value of L will then become

$$L = .298/3.18 \times 10^9 = .0937 \times 10^{-9}$$

$$L = 93.7 \times 10^{-12} \text{ Henrys .}$$

The R/L ratio for this resistor must have a value of

$$R/L = .00058/93.7 \times 10^{-12} = 6.19 \times 10^6 \text{ ohms/Henry}$$

In the case of the second system, the current waveform is shown in Figure 2.

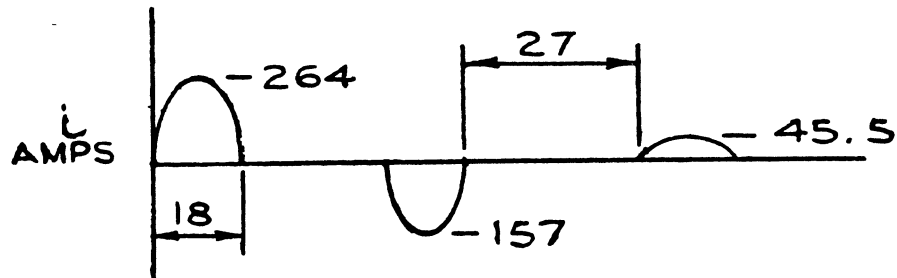


FIGURE 2.

Calculating $I^2 t_p$, one finds

Pulse	I	I^2
1	187	3.47×10^4
2	111	1.22×10^4
3	32.1	$.10 \times 10^4$

Therefore

$$\sum I^2 t_p = 4.79 \times 10^4 \times 18 \times 10^{-6} = .86 \text{ joules/ohm}$$

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The total output of this system has been found to be .260 joules. Using the 2 per cent loss limit again, the resistor loss limit is

$$U_t = (.260) (.02) = .0056 \text{ joules}$$

then the limit for R becomes

$$R = .0056/.86 = .00651 \text{ ohms}$$

The maximum voltage drop existing across this resistor will be

$$e_{\text{peak}} = .00651 \times 264 = 1.72 \text{ volts}$$

Again using the 10 per cent inductive drop limit, the drop across the inductance may go as high as

$$e_L \text{ peak} = .1 \times 1.72 = .172 \text{ volts}$$

Since for pulse 1, where the maximum will occur

$$i = 264 \sin \frac{2 \pi t}{36 \times 10^{-6}} \text{ amps}$$

then

$$di/dt = \frac{264 \times 2 \pi}{36 \times 10^{-6}} \cos \frac{2 \pi t}{36 \times 10^{-6}} \text{ amps/sec}$$

from whence

$$L = e_L \text{ peak} / |di/dt| \text{ max.}$$

$$L = .172/46.2 \times 10^6 = 3720 \times 10^{-12} \text{ Henrys}$$

In this case the R/L ratio becomes

$$R/L = .00651/3720 \times 10^{-12} = 1.75 \times 10^6 \text{ ohms/Henry}$$

DIFFERENTIATOR METHOD OF CURRENT MEASUREMENT:

Since the entire discharge current must pass through the tank capacitor, it is sufficient to measure this to determine the plug current. This capacitor, for measurement purposes, may be considered to be a pure element having no series resistance or inductance. Taking these assumptions into account and realizing that any waveform encountered in this type of measurement is composed of certain additions of sinusoidal waveforms, one may use a method of differentiation to determine the discharge current.

It is well known that the current through a capacitor is related to the voltage drop across the capacitor by the following relations. The charge on a capacitor at any time is

$$q = Ce \quad (\text{Eq. 1})$$

where q = charge on capacitor

C = capacity

e = voltage across capacitor

differentiating both sides of equation (1), one obtains

$$\frac{dq}{dt} = C \frac{de}{dt} \quad (\text{Eq. 2})$$

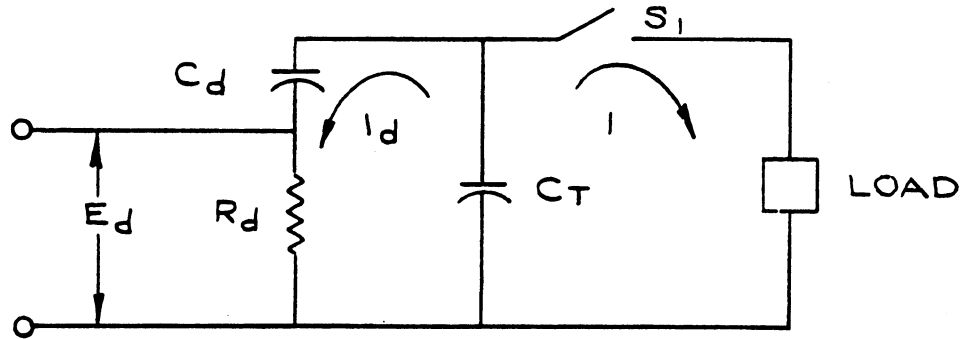
and knowing that

$$i = dq/dt$$

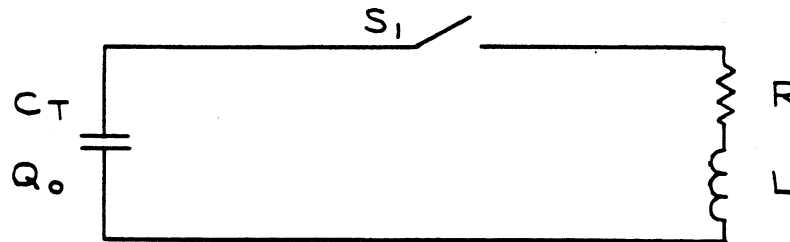
then equation (2) becomes

$$i = C de/dt \quad (\text{Eq. 3})$$

Using equation (3) as a basis of the method of measurement, a method to obtain the current through a capacitor is to measure the differentiated capacitor voltage. A simple circuit to accomplish this is shown below.



In order to establish the voltage to be differentiated, it is necessary to solve the load circuit, disregarding the measuring circuit, for current and from that current, establish the tank capacitor voltage.



A general case with a resistance and inductance for load will be considered. The equation for the series circuit consisting of L , R , and C_T is

$$L \frac{di}{dt} + iR + q/C_T = 0 \quad (\text{Eq. 4})$$

It is found that if S_1 is closed when the charge on capacitor C_T is Q_0 , then

$$i = -Q_0 \frac{(\delta^2 + \psi^2)}{1} e^{-\delta t} \sin \omega_1 t \quad (\text{Eq. 5})$$

$$\delta = R/(2L) \quad E_T = \frac{Q_0}{C_T}$$

$$\psi = \omega_1 = \sqrt{1/LC_T - (R/2L)^2} \quad (\text{Eq. 5a})$$

The solution of (4) is

$$i = -(E_T/\omega_1 L) \varepsilon^{-Rt/2L} \sin \omega_1 t \quad (\text{Eq. 6})$$

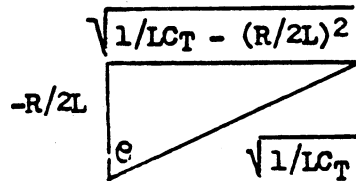
The charge on capacitor C_T at any time, t , is

$$q = \frac{Q_o \varepsilon^{-Rt/2L}}{\sqrt{LC_T} \omega_1} \sin (\omega_1 t - \theta) \quad (\text{Eq. 7})$$

Where

$$\theta = \tan^{-1} \frac{\sqrt{1/LC_T - (R/2L)^2}}{-R/2L}$$

which may be expressed graphically as



The voltage on capacitor C_T is

$$e_T = q/C_T = \frac{-E_T \varepsilon^{-Rt/2L}}{\omega_1 \sqrt{LC_T}} \sin (\omega_1 t - \theta) \quad (\text{Eq. 8})$$

$$e = \frac{-E_T \varepsilon^{-Rt/2L}}{\omega_1 \sqrt{LC_T}} [\sin \omega_1 t \cos \theta - \cos \omega_1 t \sin \theta]$$

$$e_T = \frac{-E_T \varepsilon^{-Rt/2L}}{\omega_1 \sqrt{LC_T}} \left[\frac{-R/2L}{\sqrt{1/LC_T}} \sin \omega_1 t - \frac{\sqrt{1/LC_T - (R/2L)^2}}{\sqrt{1/LC_T}} \cos \omega_1 t \right] \quad (\text{Eq. 9})$$

We will take the condition $1/LC_T \gg (R/2L)^2$

Therefore (5a) becomes

$$\omega_1 = \sqrt{1/LC_T}$$

and

$$\theta = \pi/2$$

This is a circuit with high Q since $R/2L$ is much less than $1/LC_T$. The charge and current of this system are oscillatory and are damped by an amount dependent on $R/2L$. As $R/2L$ becomes small, the damping is less than $1/LC$ of (5a) become independent of the damping. ω_1 is greatest therefore the period of oscillation is the least. Figure 5 gives the graph of current of equation (6). The graph of charge (equation 7) is the same except for its phase angle.

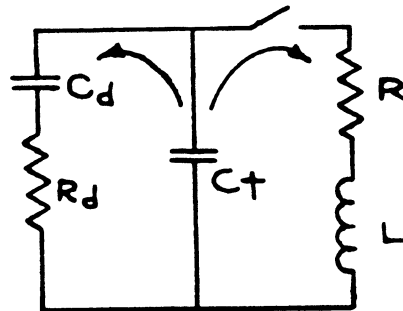
The damping can be given by $y = \varepsilon^{-Rt/2L}$ as represented by dotted lines in Figure 5:

Therefore

$$e_T = E_T \varepsilon^{-Rt/2L} \cos \omega_1 t \quad (\text{Eq. 10})$$

This voltage e_T is also the voltage across R_d and C_d in the differentiating circuit, so, neglecting the drop across C_T caused by the differentiator current

$$e_T = \frac{1}{C_d} \int i_d dt + i_d R_d$$



$$(\text{Eq. 11})$$