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Microsecond-Resolution Electrical Measurements in High-Current Discharges[1]

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The instrumentation and operation of an accurate technique for electrical measurements in a capacitor discharge system are described. Capable of measuring currents up to about 50 kA at voltages up to 10 kV, the system uses commercially available current transformers to measure both current and voltage. The measurement system was evaluated by performing experiments on a calibrated Inconel resistor. The results indicate that electrical resistance and imparted electrical energy can be measured with an uncertainly of less than 1.5%.

KEY WORDS: electrical measurements; high voltage; pulse current; pulse voltage; transient measurements.

1. INTRODUCTION

In recent years, rapid pulse heating of specimens in high-current capacitor discharge systems has been used to investigate the thermophysical properties of metals at high temperatures [1–6]. A long-standing difficulty with such systems is the accurate measurement of current and voltage for the determination of electrical resistance and imparted electrical power and energy. Typical problems include the presence of high voltages at the measuring instruments, ground-loop currents, and induced voltages in measuring circuits.

Current measurements are often made using either a coaxial shunt [3, 7–9] or a current transformer [2, 5, 10–12]. The coaxial shunt eliminates, to a large extent, the effects of induced voltages, but it still suffers from high-voltage and ground-loop problems. In addition, the shunt is

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subject to an increase in resistance with frequency due to the skin effect [2, 9, 13] and presents a relatively large load resistance to the discharge circuit. Capable of accurately measuring current pulses over a large range of amplitudes and frequencies, the current transformer offers several advantages over current measuring shunts [11]. Because its output is electrically isolated from the discharge circuit, the current transformer eliminates, to a very large extent, the problems associated with induced voltages, high voltages, ground loops, and skin effect. Also, it practically adds no load resistance to the discharge circuit.

Voltage measurements in high-current systems, typically more difficult to perform than current measurements, are often made using a resistive voltage divider [5, 14–17]. However, the voltage divider suffers the same high-voltage and ground-loop problems as the coaxial shunt. In addition, the measured voltage is subject to errors due to induced voltages in the measuring circuit. Typically, induced voltage effects are compensated for mathematically using an estimate of the total effective inductance of the specimen and measuring circuit [2, 6, 16]. Ostroumov and Shteinberg [15] and Cassidy et al. [17] used direct compensation for induced effects by placing a pickup coil in the measuring circuit which produced an induced voltage equal and opposite to that normally induced in the circuit. Moses and Korneff [14] and Seydel et al. [5] used a similar technique based on electronic amplification of the pickup coil voltage.

Other methods of measuring voltage in high-current systems include precision capacitive dividers [18] and optical methods [19–22]. Optical methods of voltage measurement, based on the Kerr, Pockels, or Faraday effects, offer complete electrical isolation from the discharge circuit. The method based on the Kerr effect is developed more than the others and is reported to be capable of voltage measurements with an uncertainty of about 1% [22].

This paper describes the instrumentation and operation of an accurate technique involving the use of commercially available current transformers to make electrical measurements in a capacitor discharge system (approximately 50 kA at voltages up to 10 kV with microsecond resolution). The system is designed for the investigation of thermophysical properties of materials at high temperatures. A novel feature of this technique is the use of a current transformer to permit accurate measurements of voltage during the capacitor discharge experiments. Physical compensation of induced voltages is accomplished by using a pickup coil in the voltage measuring circuit in a manner similar to that described by Ostroumov and Shteinberg [15] and Cassidy et al. [17]. The results and associated errors in measurements of electrical resistance and imparted electrical energy to a calibrated Inconel resistor are described.

2. DESCRIPTION OF THE SYSTEM

A functional diagram of the capacitor discharge system used to determine electrical resistance and energy imparted to electrically conducting specimens is shown in Fig. 1. The specimen, represented by resistance R_s, is connected in series with a 24-kJ (120-μF, 20-kV) capacitor bank. For metallic specimens, R_s is typically only a few milliohms and the discharge circuit behaves as an underdamped RLC circuit with exponentially damped oscillations at a nominal frequency of 10 kHz (upper trace in Fig. 2). The oscillatory nature of the circuit can be minimized by operating it in a crowbar mode using switch 2. In crowbar operation, switch 2 is closed just after the circuit current reaches its initial peak value. This creates a short across the specimen and allows the energy stored magnetically during the initial rise of the current to be returned to the circuit as unidirectional current (lower trace in Fig. 2). Both switches are high-voltage mercury vapor ignitron tubes. The capacitor bank and the discharge circuit are physically housed in a completely shielded room. All the electronic components and instruments, including the high-voltage power supply, timers, data acquisition system, and computer, are placed in a control center outside the shielded room.

2.1. Current Measurement

The current measuring circuit consists of a current transformer (CT-1) rated to 50 kA, a 50-Ω noninductive voltage divider (nominal ratio, 50: 1),

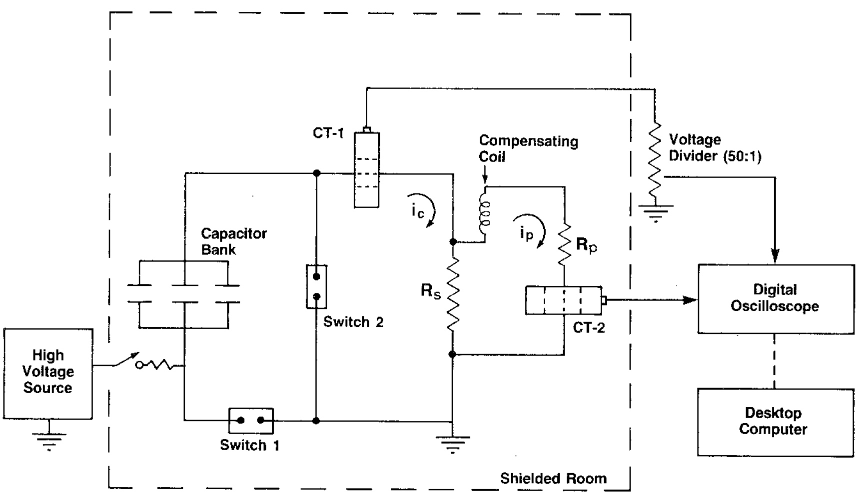

Fig. 1. Functional diagram of the capacitor discharge system including the current and voltage measuring circuits.

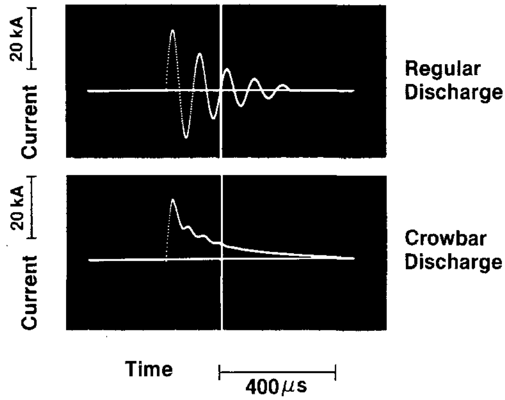

Fig. 2. Oscilloscope trace photographs of current waveforms for oscillatory (upper trace) and crowbar (lower trace) capacitor discharge conditions.

and a digital oscilloscope. The nominal sensitivity of the current transformer connected to a 50-Ω load is 0.005 V/A. Accurate values for the sensitivity of the current transformer and the divider ratio were obtained by calibration.

2.2. Voltage Measurement

The voltage measuring circuit consists of a high-resistance path connected in parallel across the specimen. The total dc resistance of the parallel path, approximately 1000 to 10,000 times larger than the specimen resistance R_s, is represented in Fig. 1 by R_p. Although the voltage across the parallel path is equal to that across the specimen, both voltages include several inductive components. These inductive components can be compensated for and effectively cancelled out by inserting into the parallel circuit a small coil which is electromagnetically coupled to the main discharge circuit. Called the compensating coil in Fig. 1, the proper orientation of this coil for compensation of inductive effects can be determined by simplifying the circuit equation for the parallel circuit. This equation is given by

$$(i_c - i_p) R_s + L_s \frac{d}{dt}(i_c - i_p) + M \frac{di_c}{dt} - M_c \frac{di_c}{dt} - i_p R_p - L_p \frac{di_p}{dt} = 0 \quad (1)$$

where i_c is the instantaneous current in the main discharge circuit, i_p is the instantaneous current in the parallel path circuit, L_s is the self-inductance of the specimen, M is the mutual inductance between the main discharge circuit and the parallel circuit, M_c is the mutual inductance between the main discharge circuit and the compensation coil, and L_p is the total self inductance of the parallel path. The instantaneous currents in each circuit can be represented by the damped exponential functions

$$i_c = I_0 e^{kt} \sin \omega t \tag{2a}$$

$$i_p = I_p e^{kt} \sin(\omega t + \phi) \tag{2b}$$

where I_0, I_p, and k are constants and ϕ is the phase angle of the parallel path current with respect to the main discharge current. After Eqs. (2a) and (2b) are substituted into Eq. (1), it can be shown that the phase constant ϕ becomes zero when the mutual inductance of the compensating coil has a value given by

$$M_c = M + \frac{R_p L_s - R_s L_p}{R_p + R_s} \tag{3}$$

When this expression is substituted into Eq. (1), the circuit equation reduces to the following simple form:

$$i_p R_p = (i_c - i_p) R_s \tag{4}$$

Thus, complete compensation for inductive effects across the specimen occurs when the compensating coil is adjusted to bring the parallel path current in phase with the main discharge current. When this phase match occurs, the resistive component of voltage across the specimen is determined directly by measuring $i_p R_p$. This voltage is then used in the computation of specimen resistance and imparted power.

Because the ratio R_s/R_p is always very small, the phase compensation condition given by Eq. (3) is a weak function of specimen resistance. Thus, it can be concluded that this method of measuring specimen voltage is relatively insensitive to order-of-magnitude changes in specimen resistance.

The compensating coil is a five-turn circular coil, 4 cm in diameter, mounted with its center approximately 5 cm from a section of the main discharge circuit. The magnitude of its induced voltage is varied by rotating the area of the coil with respect to the direction of the magnetic flux produced by the main circuit.

The current in the parallel path is measured using a second current transformer (CT-2) connected to the digital oscilloscope. The parallel path current is passed twice through the current transformer, giving it a nominal output of 0.02 V/A. Accurate values for the sensitivity of the transformer and the parallel path resistance R_p were obtained by calibration.

2.3. Data Acquisition

A digital oscilloscope is used for data acquisition. It has two channels (12 bit) and is capable of recording 2048 points per channel at 1 MHz (1-μs resolution). It also has x–y display which is used to make an immediate check of the phase difference between the two measured current waveforms. The digital oscilloscope is directly interfaced to a desktop computer for data analysis. The computer has a graphics capability which permits immediate graphical presentation of computed results.

3. EXPERIMENTAL METHOD

To test and characterize the accuracy of the measuring system, a calibrated tubular resistor (made of Inconel) was used as the specimen. The Inconel resistor has the following dimensions—length, 23.10 cm; outer diameter, 2.54 cm; and inner diameter, 2.22 cm—and a resistance of 3.0777 mΩ.

Most of the experiments performed were of the oscillatory type (not crowbar mode) since this type represents the severest test of the measurement technique. Measured current and voltage data from the first three cycles of oscillation were used to compute electrical resistance and imparted electrical power and energy. By comparing the experimental values of electrical resistance and imparted energy with the expected values for the calibrated resistor, an estimate of the accuracy of the measurement system was obtained.

Capacitor discharge experiments were conducted at nominal initial capacitor voltages of 3, 5, and 8 kV. These levels, arbitrarily called low, mid, and high ranges, produced maximum peak discharge currents of approximately 15, 35, and 54 kA, respectively. Experiments were conducted using four different values for the parallel resistance. The nominal values of R_p were 2, 5, 10, and 20 Ω. These resistance values were achieved with series-parallel networks using 10-W noninductive resistors.

A total of 52 experiments was conducted on the calibrated resistor: four experiments at the low range and two experiments each at the mid and high ranges for each value of R_p, eight experiments at selected ranges for the 5- and 10-Ω resistances, and a second set of two experiments at each range for the 2- and 5-Ω resistances. The duration of these experiments ranged from 312 to 319 μs. The maximum peak voltage across the parallel path resistance ranged from approximately 47 to 166 V, and the maximum peak current in the parallel path ranged from approximately 3 to 76 A.

In addition to the above experiments, several experiments using the crowbar mode of discharge were conducted to study phase matching using unidirectional currents.

3.1. Calibration

Both current transformers were calibrated *in situ*. Current transfomer CT-1 was calibrated using a high-current steady-state ac power supply and a 0.01-Ω standard resistor connected to the main discharge circuit. The current through the transformer was accurately determined by measuring the voltage across the standard resistor. A frequency of 2.5 kHz was used to avoid waveform distortions that occurred in the power supply at high frequencies. Measurements using steady-state ac current amplitudes in the range 14 to 24 A yielded an average sensitivity for CT-1 of 0.004850 V/A.

Calibration experiments similar to those described above were carried out on current transformeer CT-2 using the ac power supply and a 0.1-Ω standard resistor. Measurements using steady-state ac current amplitudes in the range 2.2 to 14.5 A yielded an average sensitivity for CT-2 of 0.02003 V/A.

The ratio of the voltage divider in the current measuring circuit was determined by connecting a dc voltage standard across its input and measuring its output voltage using a six-digit precision digital multimeter (DDM). The measurements yielded a ratio of 48.08: 1.

The resistance of the parallel path was measured by disconnecting the circuit from the specimen and connecting it to the ohmmeter scale of the precision DMM. The results of these measurements yielded values for the parallel resistance of 2.178, 5.104, 9.980, and 20.10 Ω, respectively.

3.2. Phase Matching

Most experiments were preceded by a series of experimental trials in which the compensating coil was adjusted to bring the current in the parallel path into phase with that in the main discharge circuit. The relative phase shift between the two currents as measured by CT-1 and CT-2 was easily monitored using the Lissajous pattern displayed by the x–y display feature of the digital oscilloscope. Figure 3 shows oscilloscope traces of the current waveforms and their associated x–y displays for three trial experiments. Before any compensation is added to the parallel circuit (Fig. 3a), the current in the parallel path (upper trace) clearly leads the main discharge current (lower trace). This phase difference is represented dramatically as an elliptical spiral when displayed in the x–y mode. Figure 3b shows the situation when the coil is adjusted for partial compensation, and Fig. 3c shows the results when complete compensation is obtained. Because the digital oscilloscope has the facility to expand each scale of the x–y display up to a factor of 64, it is estimated that the phase match can be achieved to better than 0.5°.

(a)
(b)
(c)

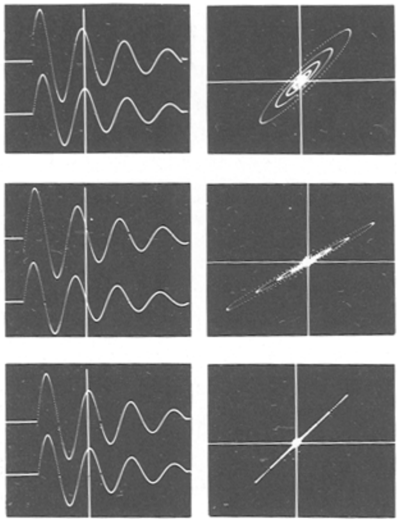

Fig. 3. Oscilloscope trace photographs of the parallel path current (upper trace) and the main circuit current (lower trace) and the associated x–y display for (a) no phase match, (b) partial phase match, and (c) complete phase match.

As the experimental range was increased from low to high, the phase match did not require adjustment except in those cases where the amplification setting of the two channels of the oscilloscope differed by a decade. In such cases, the oscilloscope itself introduced a phase shift of approximately 0.5° between its two channels. When such phase shifts occurred, a new phase match was made. In agreement with Eq. (3), the angular position of the compensation coil had to be increased as the value of R_p was increased from 2 to 20 Ω.

4. RESULTS

Each experiment yielded point-by-point values for electrical resistance and imparted power for the first three cycles of oscillation. These data were used to compute an average value of specimen resistance and imparted electrical energy which were compared to the expected values for these quantities. Since the maximum temperature rise of the calibrated Inconel resistor was never more that 50°C, its electrical resistance was essentially constant throughout all experiments.

4.1. Electrical Resistance

To determine an average value of electrical resistance for each experiment and to reject data near the zero crossing points of current and voltage, only data points where the voltage was larger than 25% of the voltage amplitude of the first peak of the oscillations were used. This reduced the number of points used in each computation of average resistance to about three-fourths of the total number of recorded data points.

The measured average resistance in these experiments varied from 3.072 to 3.087 Ω. All values were well within 1% of the known value. In all cases, the standard deviation of the experimental data was larger than the absolute deviation from the known value. If the results of electrical resistance from all 52 experiments are averaged, the overall average yields a value of 3.078 Ω, with a standard deviation of 0.12%. The maximum absolute deviation of any result from this average is 0.3%.

The experiments show no systematic variation between the average resistance for a given range and the value of R_p. They also show no systematic variation with range except for the experiments where $R_p = 2\Omega$. For this value of parallel resistance the average resistance decreased with increasing range. However, the difference between low and high ranges is less than 0.3%.

4.2. Electrical Power and Energy

For each experiment, the instantaneous power imparted to the calibrated resistor was obtained from the product of measured voltage and current. The energy imparted to the resistor was computed by numerically integrating the instantaneous power over the duration of the experiment.

Since the resistance of the calibrated resistor remains constant during an experiment, it was possible to compare the imparted energy as computed by $\sum VI$ with that as computed by $\sum I^2R$, where R is the known resistance of the resistor. If it is assumed that the current is accurately measured, the comparison of $\sum VI$ with $\sum I^2R$ provides an indication of the accuracy of the voltage measuring technique. For all the experiments, the two methods agreed with one another to better than 1%.

4.3. Crowbar Mode Experiments

Several experiments using crowbar discharge conditions were conducted with R_p equal to 5 and 20 Ω. Because the unidirectional currents have a small oscillatory nature, the degree of phase matching could still be determined using Lissajous patterns. It was observed that the phase match was independent of the type of discharge and, further, that the results for resistance and imparted energy from crowbar discharge experiments are relatively insensitive to modest variations ($\pm 5°$) in the orientation of the compensating coil. The latter result is to be expected because inductive effects are much reduced for unidirectional current waveforms. These results suggest that in experimental conditions where crowbar discharges are desired, effective phase matching can be achieved using preliminary low-voltage discharges in the oscillatory mode.

5. ERRORS

Errors associated with measured quantities are discussed in the following sections. Wherever errors are combined to express the overall uncertainty associated with a computed quantity, the errors are expressed in percentage and an effective rms estimate of uncertainty is computed. Based on the uncertainties discussed below, the estimated uncertainty in the computed values for current and voltage is 0.8%, each. These yield an uncertainty of about 1.2% for resistance and energy. A summary of the uncertainties associated with the experimental quantities is presented in Table I.

5.1. Errors Associated with Calibration

Both current transformers were calibrated using standard resistors and a 12-bit digital oscilloscope. The uncertainty associated with either

Table I. Summary of the Uncertainties (in %) in the Experimental Quantities

Calibrated parameters	
Sensitivity of CT-1	0.6
Sensitivity of CT-2	0.6
Divider ratio	0.2
Parallel path resistance	0.2
Other measured quantities	
Phase mismatch	0.2
Voltage output, CT-1	0.5
Voltage output, CT-2	0.5
Computed quantities	
Current through specimen	0.8
Voltage across specimen	0.8
Average resistance	1.2
Energy, $\sum VI$	1.2

standard resistor is 0.05%. The uncertainty associated with measurements using the digital oscilloscope depends jointly upon quantization effects related to the digitization process and nonlinearities in the vertical amplifiers. Determined experimentally using a dc voltage standard, the maximum uncertainty associated with the digitization process was 0.3% and the uncertainty due to the oscilloscope amplifiers was 0.2%. Combining these effects, the maximum overall uncertainty associated with measurements using the digital oscilloscope was estimated to be 0.4%.

Another source of error related to calibration of the current transformers is the reliability of the calibration when extended to higher currents or higher frequencies. Since from theoretical considerations [11] the sensitivity of current transformers is expected to be independent of the magnitude of the measured current and constant for a wide range of frequencies, it was assumed that the calibrated sensitivities were accurate in the experimental ranges.

Combining all the uncertainties related to the calibration of the current transformers, the uncertainty in the measured sensitivity of either transformer is estimated to be 0.6%.

The voltage scale of the six-digit precision digital multimeter (DMM) was compared to a dc voltage standard and its ohmmeter scale was compared to a precision Wheatstone bridge. The uncertainty associated with the divider ratio is 0.2% and that associated with the parallel path resistance is 0.2%.

5.2. Errors Associated with Phase Matching

Uncertainties associated with matching the phases of the two currents arise from actual phase differences between the two waveforms and apparent phase differences produced by the measuring apparatus. The specifications for the current transformers indicate that at 10 kHz the phase difference between their output and input is less than 0.5°. The voltage divider was specially designed to have a low inductance and it showed no measurable phase difference between input and output for a 10-kHz sinusoidal waveform when tested on an analog oscilloscope.

The two channels of the digital oscilloscope showed a maximum phase difference of about 0.5° when the two channels were set at gains that differed by a decade. Trial experiments in which the phase was purposely allowed to be mismatched by approximately 0.5° suggest that the associated error in average specimen resistance and imparted energy is 0.2%. The overall uncertainty due to the phase matching process is estimated to be 0.2%.

5.3. Errors Associated with Skin Effect

For tubular conductors the skin effect is a function of the radius of the cylinder, the thickness of the tube, the frequency of the current, and the electrical resistivity of the conductor [23]. Computations show that the resistance increase in the Inconel resistor due to skin effect is much less than 0.1%.

Similar computations for the wire and resistors in the parallel path show that the increase in R_p due to the skin effect is less than 0.03%.

5.4. Errors Associated with Data Acquisition

The errors associated with using the digital oscilloscope to measure voltage and current include those errors discussed above and an error associated with determining the zero level of voltage for both channels. The estimated uncertainty associated with determining zero levels was found experimentaly to be 0.2%. Combining the errors, the overall estimated uncertainty in the measured values of current or voltage is 0.5%.

6. DISCUSSION

In this paper, we have described an accurate technique to measure electrical quantities in a high-current capacitor discharge system. The method of measuring voltage across the specimen depends upon orienting a compensating coil such that the parallel path current is in phase with the current in the main circuit. In the present system this was accomplished by displaying the damped oscillations as a Lissajous pattern on an x–y display. This method is also expected to be effective when applied to small metallic specimens where the resistance changes as the specimen heats. In addition, the method is relatively insensitive to small errors in the orientation of the compensating coil. In experiments where the phase was purposely mismatched by as much as $\pm 2°$, measured results were within expected accuracy. In the case where the system is used to generate unidirectional pulses, the same phase matching technique can be applied to preliminary low-voltage discharges in the oscillatory mode.

The results for average resistance and imparted energy are essentially independent of the current in the parallel path when the current in the parallel path is 1000 to 10,000 times less than the main discharge current. In actual thermodynamic experiments, the resistance of a metallic specimen would rapidly increase during a discharge experiment causing the proportion of current in the parallel path to increase. Since the inductance of the specimen will not significantly change during this period, the rapid change of specimen resistance is not expected to affect the measurement technique. Even if the specimen is heated into the liquid phase, self-inductance and mutual inductance changes are expected to be small and there will be little effect on the phase of the parallel path current. Thus, it is expected that phase compensation done on a real specimen at low current levels will be valid at large current levels. The experimental results show that electrical resistance and imparted energy can be measured with an uncertainty less than 1.5%.

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