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HIGH-CURRENT MEASUREMENT TECHNIQUES

J. D. Ramboz and D. R. Flach

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Electronics and Electrical Engineering
Electrosystems Division
Washington, DC 20234

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HIGH-CURRENT MEASUREMENT TECHNIQUES

J. D. Ramboz and D. R. Flach

Abstract

The measurement of very high ac currents presents special problems in the selection of current sensors, instrumentation, and techniques. This report discusses initial test results for Rogowski coils and high-capacity current shunts often used to measure large ac currents. Eight Rogowski coils of three sizes and ratings were tested at a nominal current of 1000 A. The coils were compared against an NBS precision air-core mutual inductor to obtain a measure of complex sensitivity, positional sensitivity, gap-separation sensitivity (for the split-coil types), and proximity effects of the return conductor and of ferromagnetic material. The shunt was tested to assess the proximity effects of the return conductor and of ferromagnetic material. It was concluded that the particular Rogowski coils tested would not have measurement uncertainties of less than a few percent unless extreme care was taken in their calibration and subsequent use. The measurements for the shunt suggest somewhat less proximity effect than those for the coils. A digital oscilloscope was evaluated for possible use as a transient recorder. The effective number of bits, the differential linearity, and the response to a step function were determined.

Keywords: ac current measurement; calibration; current shunts; digital oscilloscope; high current; Rogowski coils.

1. INTRODUCTION

The goal of this overall effort is to study the feasibility of accurate measurement of very high currents, up to 400,000 amperes, having short durations in the millisecond time intervals. Such currents are used in welding processes. Development of measurement techniques, development of measurement apparatus, and the evaluation of both hardware and software used for the measurement and evaluation of high-pulsed currents are being pursued.

This report discusses the first efforts to assess some of the characteristics of commercial high-current measuring instruments, namely Rogowski-type air-core coils [1], and separately, a high-current, low-impedance shunt. Test currents used were steady-state sinusoidal and limited to 2000 amperes. Also investigated was a digital-oscilloscope measurement system which may prove useful as a transient recording and display device for future efforts.

The Rogowski coils investigated were commercial units and are of a simple toroidal design. All have an air core and generate an output voltage directly proportional to the time rate-of-change of current, as

$$e_o = N \frac{d\phi}{dt} ,$$

where e_o is the coil's output voltage, N is the number of turns on the coil, ϕ is the magnetic flux produced by a current in a conductor and t is time. This can also be expressed in MKS units as

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[1] Numbers in brackets refer to the literature references listed at the end of this report.

$$e_0 = \frac{\mu_0 WN}{2\pi} \left(\ln \frac{b}{a} \right) \frac{di}{dt} ,$$

where μ_0 is the permeability of the core, W is the core width, N is the number of turns on the toroid, a and b are the inside and outside diameters of the toroid, i is the current and t is time [2]. As can be seen, the output is the time derivative of the current scaled by a constant. An electronic integrating circuit is used to process the coil's output. The output of the integrator is then directly proportional to current.

A variety of coils were selected for test. Two basic types were available; one was of a fixed geometry and the other was a split, hinged arrangement such that the toroid could be opened, placed around a current-carrying conductor, and snapped shut to its operating position. The table below gives the dimensions of the coils and the types. The coils are each arbitrarily designated by a letter which is used hereafter to identify the coil.

Table 1. Coil identification, size and type
(Size refers to the inside diameter of the toroid "window".)

Designation	Size		Type
	cm	inches	
A	12.7	5.0	Split
B	12.7	5.0	Split
C	12.7	5.0	Fixed
D	6.4	2.5	Split
E	6.4	2.5	Split
F	6.4	2.5	Split
G	6.4	2.5	Fixed
H	2.5	1.0	Split

One high-current shunt was tested to assess such effects as proximity to high-current return conductors, proximity to ferromagnetic materials, and output potential lead placement. The shunt tested has a nominal resistance of 10^{-5} ohms and a maximum current rating of 30,000 amperes with a duty cycle of 0.5%.

The oscilloscope tested utilizes digital sampling and storage techniques to record an electrical event. The oscilloscope can be remotely operated via an IEEE 488 bus by a suitable controller. Parameters such as noise, signal-to-noise ratio, differential linearity, and step response were measured.

The test results for the Rogowski coils show that current measurement could be relied upon to within a few percent over a wide variety of conditions. For measurements with uncertainties in the range of a few tenths of one percent, very tight control of the testing and calibration conditions would have to be maintained. The test results for the shunt indicate that care must be taken regarding the routing of both the high-current conductors and the potential output leads in order to keep errors below a few tenths of one percent.

Oscilloscope tests indicate that the unit tested met the manufacturer's specifications, but even so, might serve only in a limited way for the further precision measurement of pulsed currents.

2. ROGOWSKI COIL MEASUREMENTS

2.1 Comparison Bridge Circuitry

A ratio transformer bridge was configured as shown in figure 1. The primary current I was sensed by two coils and a step-down current transformer. The reference coil, made by NBS, feeds its output to an accompanying set of electronics, which gives an output voltage e_n. The coil under test feeds its output to its set of electronics producing an output voltage e_x. Both e_n and e_x are directly proportional to the current I flowing through the two coils. Current I also flows through a 5000:5 ampere step-down current transformer which, with the use of a 0.1-ohm shunt, gives a measure of primary current.
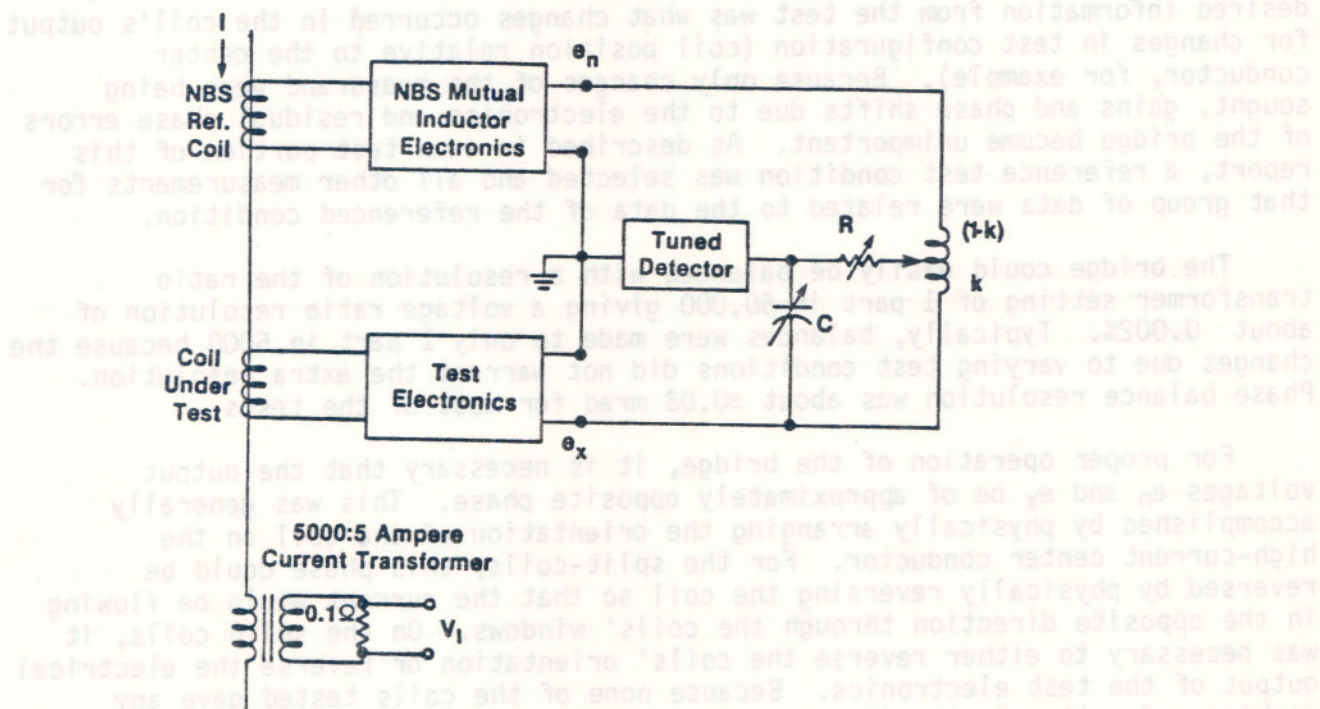
Figure 1. Bridge circuit for comparing the output voltage e_x to the reference voltage e_n.

The complex ratio of the two voltages can be derived from the ratio transformer setting k the value of R, and the value of C, when the bridge is balanced. The voltage ratio magnitude $|e_x/e_n|$ can be expressed as

$$\frac{e_x}{e_n} = \frac{k}{[(1-k)^2 + (\ RC)^2]^{1/2}}, \tag{1}$$

where ω is $2\pi f$ and all other terms are as described above. The frequency f was normally set to about 50 Hz to avoid line-frequency beat problems.

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The phase solution can be expressed as

$$\phi = \tan^{-1}[(1/k)/\omega RC] + \pi/2 \text{ radians.} \qquad (2)$$

The NBS mutual inductor electronics package has a precision voltage divider and phase adjustment built into it. These controls were set so that the magnitudes of the voltages e_x and e_n were approximately equal. This then makes $k = 0.5$ nominally and gives the bridge maximum sensitivity. The phase adjustment on the electronics package has a small and limited range used for final bridge balancing. The gross phase balance is accomplished by selecting proper values for R and C. A typical value for R was 10,000 ohms, while values for C ranged from about 0.0001 to 0.02 μF, depending on which coil was being tested. The final phase angle is then the sum of the phase shifts as determined by eq (2) and the phase setting of the mutual inductor electronics.

The absolute sensitivity of the coil under test was not measured. The desired information from the test was what changes occurred in the coil's output for changes in test configuration (coil position relative to the center conductor, for example). Because only changes of the measurand were being sought, gains and phase shifts due to the electronics and residual phase errors of the bridge become unimportant. As described in each test portion of this report, a reference test condition was selected and all other measurements for that group of data were related to the data of the referenced condition.

The bridge could easily be balanced with a resolution of the ratio transformer setting of 1 part in 50,000 giving a voltage ratio resolution of about 0.002%. Typically, balances were made to only 1 part in 5000 because the changes due to varying test conditions did not warrant the extra resolution. Phase balance resolution was about ±0.03 mrad for most of the tests.

For proper operation of the bridge, it is necessary that the output voltages e_n and e_x be of approximately opposite phase. This was generally accomplished by physically arranging the orientation of the coil on the high-current center conductor. For the split-coils, this phase could be reversed by physically reversing the coil so that the current would be flowing in the opposite direction through the coils' windows. On the solid coils, it was necessary to either reverse the coils' orientation or reverse the electrical output of the test electronics. Because none of the coils tested gave any markings of coil polarity (i.e., no "marked terminal" as is common practice of current transformers), this determination of polarity was one of trial and error.

The test current I was typically set to 1000 amperes, and, for some tests, ranged from 100 to 2000 amperes. A digital voltmeter measured the voltage V_I across the 0.1-ohm shunt as shown in figure 1. It was unnecessary to test at exact primary currents inasmuch as none of the sensing coils, electronics, bridge, etc. were grossly nonlinear. As long as ratio of the two coils' outputs was being measured with the bridge, the primary current could be varied considerably with no serious degradation of the test results.

The laboratory data recorded for each test included the following information:

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Test coil identification
Data and time of test
Test current (I)
NBS/mutual inductor electronics divider setting
NBS/mutual inductor electronics phase shifter setting
Bridge resistance (R)
Bridge capacitance (C)
Ratio transformer setting (k)
Frequency (f)
Test condition, position, orientation, etc.

The information was generally evaluated so that solutions to eqs (1) and (2) were done by computer assistance. (The program and documentation are available upon request.)

2.2 Positional Sensitivity Tests

A series of tests was performed on each of several current-sensing coils to determine the effects of the position of the high-current conductor relative to the sensing coil. The coil was mounted on a 3.2-cm (1.25-inch) diameter rod which was the high-current conductor. This passed at right angles through the coil's window. For the larger diameter coils (coils A through G), it was possible to move the coil to several positions to determine if the location of the conductor had any effect on the output.

When testing the 12.7-cm (5-inch) coils, data was collected in 17 separate positions: eight positions when the inside of the coil rested against the center conductor at angular intervals of 45°; eight positions midway radially between the center of the coil and the inside edge at angular intervals of 45°; and one position at the center of the window.

Fewer positional possibilities exist for the smaller diameter coils (coils D through G). The 6.4-cm (2.5-inch) coils were tested similarly to the 12.7-cm coils except only the outside eight positions and the central position were used, eliminating the eight intermediate radial positions. The 3.2-cm center conductor occupies a larger proportion of the window for the 6.4-cm coils than for the 12.7-cm coils leaving fewer meaningful positions available.

For the 2.5-cm (1-inch) coil (coil H), no positional tests were done because a 2.5-cm conductor was used which allowed no relative movement. A smaller conductor could not be used for the test currents of 1000 amperes because of conductor heating.

The output from the coil-under-test was compared to a reference coil by a ratio transformer bridge previously discussed. The voltage ratios (also proportional to the current sensitivity ratio) of the two coils were measured for a variety of test coil positions discussed above. For the final analysis, the data for each of the positions were compared to the data obtained at the center of the coil and the percentage difference calculated. Table 2 below gives the results for the coils tested. The maximum difference for any two positions is noted as well as the maximum difference for any position relative to the central position.

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Table 2. Test results for the positional sensitivity tests for coil A.

Coil Designation		Maximum Difference (%)	Maximum Difference Relative to Center (%)
12.7 cm (5 inch) split	(A)	7.2	-4.0
	(B)	3.7	+2.4
12.7 cm (5 inch) fixed	(C)	1.1	-0.9
6.4 cm (2.5 inch) split	(D)	1.9	-1.3
	(E)	1.4	+1.4
	(F)	1.6	-0.9
6.4 cm (2.5 inch) fixed	(G)	0.6	+0.5
2.5 cm (1 inch) split	(H)	---	---

The largest differences were measured on the larger coils, namely the 12.7-cm coils, with accordingly smaller differences measured for the smaller coils. In all instances, the split coils showed larger differences than the fixed coils.

It should be noted that the manufacturer of the coils states that the high-current conductor should occupy at least 40% of the coil's window area. This condition was not met during these tests. It is apparent that as the high-current conductor becomes a larger proportion of the window area, less relative positioning can occur until at the limit of equal diameters, no difference can exist. Table 3 below shows the diameters for the windows, the high-current conductor, and the percentage of the window area which is occupied by the high-current conductor.

Table 3. Diameters of coil windows and high-current conductor, and the percentages of the window occupied by the conductor.

Coil Designation	Inside Diameter cm	inch	High-Current Conductor cm	inch	% of Window Occupied
A,B,C Split & Fixed	12.7	5	3.2	1.25	6
D,E,F,G Split & Fixed	6.4	2.5	3.2	1.25	25
H Split	2.5	1	2.5	1	100

The high-current conductor occupied less than 40% of the window area for all coils except coil H. The diameter necessary for the conductor to be at least 40% of the window area can be calculated from the following expression (for circular cross-sectional conductors):

$$d_C > 0.632 \, d_W, \tag{3}$$

where d_C is the diameter of the high-current conductor, and d_W is the diameter of the window. The minimum diameters d_C to satisfy the 40%

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requirement for coils A, B, and C would be 8 cm, for coils D, E, F, and G would be 4 cm, and 0.6 cm for coil H.

The results shown in table 2 indicate less positional sensitivity for the 6.4-cm coils than for the larger 12.7-cm coils. The amount of window occupied for the larger coil is only about 6% as compared to 25% for the smaller 6.4 cm coils. It is presumed that the differences in position continue to decrease as the percentages of occupied window approaches 100%. A note of caution: one cannot state from the above data that the smaller coils have less positional sensitivity without further testing.

Additional tests were performed to assess the positional sensitivity of coil A when rotated about a 4.4 by 10.2-cm (1.75 by 4 inches) rectangular bar as a high-current conductor. The coil was centered about this bar and then rotated in 45° increments and measurements made. The results are shown in table 4 below. The data indicate that a maximum change of about 1.4% occurs at 90° and at 270°. Also note that for other diametrically opposed positions (namely, 0° and 180°, 45° and 225°, 135° and 315°), the changes are very nearly equal. The rectangular bar used as a high-current conductor occupied about 31% of the window area.

Table 4. Rotational sensitivity test results for a 4.4-cm by 10.2-cm rectangular bar centered in coil A window.

Rotational Position (Degrees)	% Change from Output at 0°
0	0.0
45	-0.4
90	-1.4
135	-1.3
180	-0.1
225	-0.7
270	-1.4
315	-1.0

2.3 Gap Separation Sensitivity

A group of measurements was made on two of the 12.7-cm coils to determine the effects of the split coil not being completely shut. The coil was placed in three positions about the high-current conductor which passed through the coil's window. In the "upper" position, the conductor was located so that the top of the conductor rested against the inside top of the coil directly adjacent to the split opening of the coil. The second position was located in the center of the window. The "lower" position was selected such that the bottom of the conductor was resting against the lower inside of the coil directly adjacent to the hinged split. The coil was placed in the upper position and remained there while the split coil was opened in increments of 1.3 cm (0.5 inch) from closed to 12.7 cm (5 inches). The coil output was compared to the NBS reference coil for each gap setting. The same procedure was followed for the center and lower positions of the conductor. The ratio and phase angle of the coil's output relative to the NBS reference coil were calculated. Table 5 below gives the test results and figure 2 shows the gap setting data plotted for coil A.

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%
D
E
C
R
E
A
S
E

U = Upper Position
C = Center Position
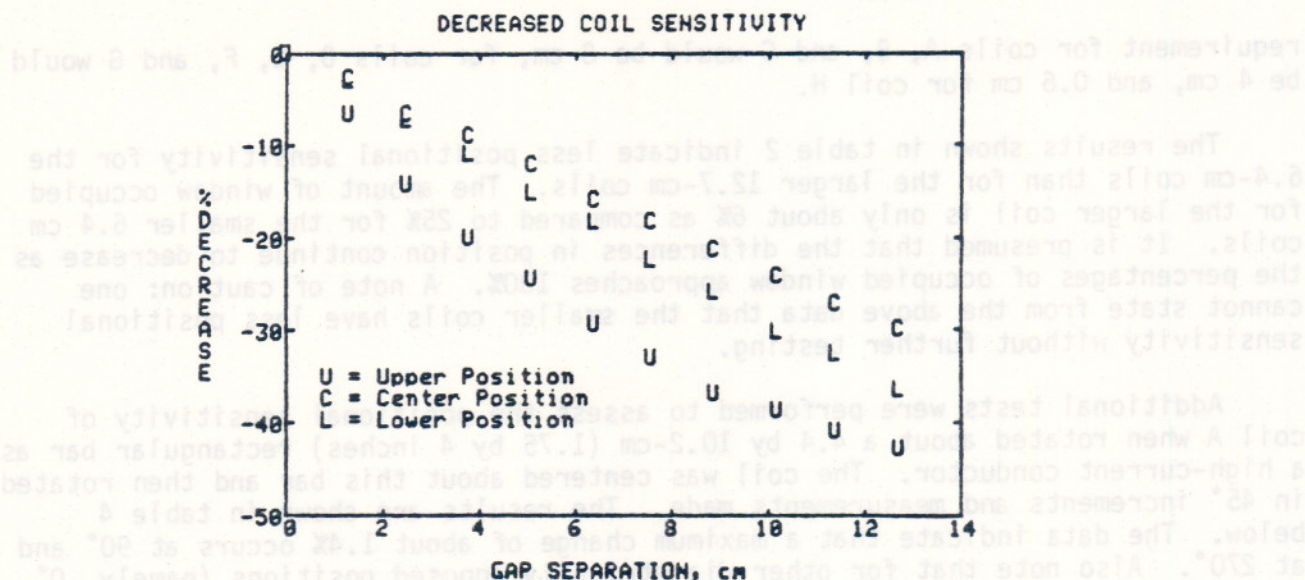L = Lower Position

GAP SEPARATION, CM

Figure 2. Decrease of coil sensitivity for gap separations and three positions
of the high-current conductor (coil A).

Table 5. Test results for coil A when split coil is opened
in increments of 1.3 cm (0.5 inch).

| Gap Opening | | % Decrease of Coil Output | | |
cm	Inches	Upper Position	Center Position	Lower Position
0	0	0.0	0.0	0.0
1.3	0.5	6.7	2.8	3.1
2.5	1	14.4	6.8	7.4
3.8	1.5	20.1	9.1	11.0
5.1	2	24.6	12.2	15.2
6.4	2.5	29.5	16.0	18.4
7.6	3	33.1	18.4	22.6
8.9	3.5	37.0	21.4	26.0
10.2	4	38.8	24.3	30.3
11.4	4.5	41.0	27.3	32.6
12.7	5	42.9	30.0	36.5

The gap can open to approximately 18 cm (7 inches); however, when this was
first done, a ground wire broke in the region of the hinge mechanism and the
coil became sensitive to the proximity of nearby objects, such as hand motion
near the coil, etc. The coil ground was repaired and the gap opening was
thereafter limited to about 12.7 cm (5 inches).

Similar data were obtained from the 12.7-cm split coil designated as
coil B. The high-current conductor was about 3.2 cm in diameter. The least
sensitive position to gap opening was in the center of the window. The most
sensitive of the three positions tested was at the "upper" side of the window
nearest the split. It should be noted that wide-gap settings are abnormal to
the coils use. The wide-gap measurements confirmed a fair degree of linearity
of sensitivity decrease with gap opening, therefore, data from the wide-gap
measurements could be used for linear extrapolation to small-gap openings. The
extrapolated sensitivity decrease for small-gap separations is about 0.1% per
0.025 cm (0.01 inch).

Gap opening tests were run with a high-current conductor occupying only about 6% of the window area; it is felt that the sensitivity to gap opening would be somewhat less had a larger conductor been used. Also, these tests were performed in the NBS 12,000-ampere current cage where rather symmetrical electric fields exist; in situations where distorted fields are present, gap opening sensitivity could be much worse.

2.4 Return Conductor Proximity Effects

Five coils were tested for external field effects by using a flexible, 2.5-cm diameter high-current conductor. The conductor was passed through the coil's window at an arbitrary position. This position was left unchanged for the set of measurements on any one coil. The distance between the conductor in the window and the return high-current conductor was varied from a distance of about 51 cm (20 inches) to about 5 to 10 cm (2 to 4 inches) minimum, depending on the particular coil being tested.

The coils selected for these tests ranged from the smallest to the largest (2.5 cm to 12.7 cm) and consisted of one fixed coil and one split coil from each size group. The output at the most distant position of the return conductor was used as the reference value to which all other data were compared for each coil. The test results are shown in table 6. The percentage change in output is shown in columns for each coil tested. Data is presented vertically against distance between high-current conductors.

Table 6. Return conductor proximity effects. Test results of percent change in coil sensitivity as a function of distance to return current conductor.

Approximate Distance Between High Current Conductors cm	Inches	Percent Change Referenced to Most Distant				
		2.5 cm Split Coil H	6.4 cm Fixed Coil G	6.4 cm Split Coil D	12.7 cm Fixed Coil C	12.7 cm Split Coil A
74	29	0.0				
51	20	-0.2	0.0			
48	19		+0.2		0.0	
46	18					0.0, 0.0
43	17					
41	16			0.0	-0.7	
38	15		+0.3			+0.2
36	14					
33	13				-0.1	
31	12	-0.5	+0.4		+0.1	
28	11			-0.7		
26	10				+0.4	
23	9	-0.8			+1.2	0.0
20	8		+0.3			
18	7	-0.9			+0.7	-0.6
15	6				+3.3	
13	5	-1.4		-0.5	+0.8	-4.3
10	4	-1.9	+0.3			-8.0
7.6	3			-0.5	+0.3	
5.1	2	-2.9	+0.7			
2.5	1					

The data suggest that, in most instances, the greatest change in coil output occurs when the return conductor is brought closest to the coil. Generally, the split-coil types exhibited a greater sensitivity to the close proximity of the return conductor than the fixed-coil types. This was especially evident for the 12.7-cm split coil versus the 12.7-cm fixed coil.

Coil A was tested twice for this effect. The first set of values shown was obtained when the coil was oriented about the high-current conductor such that the two opposite sides of the coil rested against the conductor. The second set of values was obtained when the conductor passed through the window perpendicularly. As can be seen from the data, a vast difference in results can be obtained depending on the location and orientation of the coil with respect to the high-current conductor passing through the coil's window.

In general, it would appear that changes of coil output are less than a few tenths of one percent for conductor separation greater than about 51 cm (20 inches). When the separation is less than about 15 cm (6 inches), larger changes can be expected, especially for the split coil types.

2.5 Effects of Ferromagnetic Materials in Coil Proximity

Four of the coils were tested for the effects of ferromagnetic material in the proximity of the coil being tested. A loop approximately 51 cm (20 inches) in diameter was arranged using 2.5-cm flexible conductor. One side of the loop passed through the coil being tested. A steel plate 24 by 52 cm (9.5 by 20.5 inches) was placed near the coil and was either on or in the 51-cm loop. The plate was 1.4 mm (0.050 inch) thick. The first position of the plate was in a plane parallel to the plane on the loop and perpendicular to the coil being tested. The second position was in a plane perpendicular to both the loop and the coil. For one test, the plate was brought alongside the coil in a plane parallel to the coil.

The results of this series of measurements are shown in table 7. The overall effect on the fixed coils was very small, less than a few tenths of one percent in the worst case. The split coils showed the largest changes when the plate was in the coils' proximity.

Table 7. Effect of ferromagnetic plate in proximity of coil.

Coil Designation	Percent Change Referenced to No Ferrous Material		
	Perpendicular Horizontal	Perpendicular Vertical	Parallel
6.4 cm, fixed, Coil G	-0.04	-0.08	-0.32
6.4 cm, split, Coil D	-0.24	-0.56	-----
12.7 cm, fixed, Coil C	0.00	0.00	-----
12.7 cm, split, Coil A	-1.8	-3.1	-----

2.6 Relative Coil Sensitivity

The data for each of the seven coils were evaluated for their individual sensitivity as compared to the NBS reference coil. The values represent a factor of the uncalibrated NBS coil's sensitivity. Using such data, relative comparisons can be made, one coil with respect to another, to determine how consistently the coils are manufactured. Table 8 gives the data.

For coils A through G, the mean sensitivity ratio relative to the NBS reference coil was 0.3790 with a one standard deviation of ±0.0051 (±1.4%) about the mean. The maximum difference between any two coils of the group A through G was about 3%. Coil H is a high sensitivity coil whose output was approximately 7.5 times greater than the other coils. For coils A through C, the value shown in percent following the sensitivity ratio is a one standard deviation limit for the data from which the mean sensitivity ratio was calculated.

Table 8. Sensitivity of each coil relative to the NBS reference coil. Sensitivity given to four significant digits followed by one standard deviation where meaningful data existed.

Coil Designation	Sensitivity[a] Ratio Relative to NBS Coil
Coil A (12.7 cm, split)	0.3831 ±1.1%, 0.3942[b] ±0.3%
Coil B (12.7 cm, split)	0.3841 ±0.3%
Coil C (12.7 cm, fixed)	0.3705 ±0.1%
Coil D (6.4 cm, split)	0.3760
Coil E (6.4 cm, split)	0.3751
Coil F (6.4 cm, split)	0.3825
Coil G (6.4 cm, fixed)	0.3815
Coil H (2.5 cm, split)	2.806 [c]

[a] Value obtained with use of 3.2-cm round conductor in all tests unless otherwise noted.
[b] High-current conductor dimensions used were 4.4 x 10.2 cm.
[c] High-current conductor was 2.5-cm diameter.

3. HIGH-CURRENT SHUNT MEASUREMENT RESULTS

Preliminary measurements were made on a 30,000 ampere shunt which has a nominal value of resistance of 10 microhms. It is rated at a duty cycle of 0.5% for a period of one second. The maximum steady state current is rated at 1,500 amperes.

Tests were performed to assess 1) the proximity effects of the return high-current conductor, and 2) the proximity effects of ferromagnetic materials (i.e., steel plates, etc.). To test for the proximity effects of the return high-current conductor, the shunt was connected into a 1,000 ampere circuit with flexible 2.5-cm cables. A flat loop was configured having an approximate diameter of 50 cm. The loop was made decreasingly smaller in increments and measurements were made of the complex voltage ratio of the shunt's output compared to the output of the NBS reference coil through its accompanying electronics.

The basic ratio transformer bridge shown in figure 1 was used to measure the magnitude of the voltage ratio and the phase angle. A high input impedance amplifier having a gain of 10 was used to provide more voltage from the shunt's output and its output was fed to the bridge circuit as voltage e_x.

Table 9 gives the measured results of the return conductor proximity effects. The percentage change in voltage ratio is referenced to the value measured at a separation of conductors of 51 cm (20 inches). The phase angle difference is also referenced to the value measured at the 51-cm separation.

The changes were relatively small from the initial separation of 51 cm to 20 cm, however, as the separation became less than 20 cm, the phase angle showed significant changes and the percentage change in ratio began to decrease rapidly. The ratio changed in a rather smooth function, finally decreasing about -0.46% from its initial value. The change in phase difference, however, increased rather smoothly until the separation was nearly zero, then suddenly reversed when zero separation was reached.

Table 9. Shunt measurement results to assess the proximity effects of the return high current conductor.

Approximate Distance Between Shunt and Return Conductor		Change Referenced to 51 cm	Phase Angle Difference Referenced to 51 cm
cm	inches	Separation (percent)	Separation (mrad)
51	20	0.00	0.0
46	18	+0.02	+0.2
41	16	+0.03	+0.3
36	14	+0.04	0.0
31	12	+0.05	+0.3
25	10	+0.05	+0.6
20	8	+0.04	+0.8
15	6	+0.01	+2.6
10	4	-0.05	+4.4
7.6	3	-0.10	+6.9
5.1	2	-0.18	+10.5
2.5	1	-0.27	+14.3
0	0	-0.46	-4.2

The configuration for the measurement of ferromagnetic proximity effects used the same bridge measurement arrangement as discussed above. Basically, a reference measurement was made to establish some arbitrary value for ratio and phase. This reference condition was an open 51-cm loop of high-current conductor with the shunt connected in one side of the loop. A 24- by 52-cm steel plate was then brought into the vicinity of the shunt and loop and a new bridge balance obtained. The differences from the initial conditions were then calculated. Table 10 gives the measurement results. Also shown are the results of two other tests: one to assess the effects of the location of the coaxial cable coming from the shunt and crossing the high-current conductor, and the other to evaluate the pickup effects of the "compensation" network and enclosure which is attached to the coaxial cable coming from the shunt.

Table 10. Effects of ferromagnetic material in the proximity of the shunt. Also shown are effects due to coaxial cable location and "compensation" network pickup.

Change in Ratio Relative to Reference Condition Listed (percent)	Difference in Phase Angle Relative to Reference Condition Listed (mrad)	Test Condition
0.00 (ref)	0.00 (ref)	51-cm open flat loop, no ferromagnetic material present.
+0.07	-0.2	Ferromagnetic plate flat on loop.
+0.15	-2.3	Ferromagnetic plate upright in loop 25 cm from shunt.
+0.34	-6.9	Ferromagnetic plate upright against end of shunt.
-0.28	+8.7	Ferromagnetic plate flat on shunt.
0.00 (ref)	0.0 (ref)	51-cm open loop, coaxial cable perpendicular to and on return conductor.
+0.04	+0.6	Coaxial cable perpendicular to and 23 cm above return conductor.
+0.10	+0.6	Coaxial cable parallel to and 23 cm above return conductor.
+0.11	-4.5	Coaxial cable parallel to and on return conductor for a length of 38 cm.
0.00 (ref)	0.0 (ref)	Network enclosure magnetically shielded.
0.00	+0.8	Network enclosure magnetically shielded on five sides - small magnetic "leaks."
+0.11	+20.9	Network enclosure placed next to return conductor, no magnetic shielding.

The effect of ferromagnetic material in the general proximity of the shunt gave measurable changes, but were not considered too great in comparison to a few tenths of one percent unless the material came very close to the shunt.

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The coaxial voltage-sensing lead coming from the shunt is sensitive to pickup when placed near the high-current conductor, especially if it is parallel to the conductor. It should be kept at least 20 cm from the conductor and, if necessary to be that close, be oriented at right angles to the conductor. (The manufacturer recommends that this lead be kept 2 or 3 ft away from high-current conductors.)

The compensation network which is enclosed in a small aluminum box is very sensitive to stray pickup if anywhere near a high-current conductor. Distances up to 60 to 100 cm showed significant pickup. Simple magnetic shielding (placing the "box" in a steel enclosure) reduced the pickup to barely measurable levels.

4. DYNAMIC TESTS ON A DIGITAL OSCILLOSCOPE MEASUREMENT SYSTEM

4.1 Sinewave Testing

The digital-oscilloscope measurement system was tested for its signal-to-noise (S/N) ratio using a sinusoidal source as the input stimulus over the frequency range from 1 kHz to 10 MHz. A sinewave fitted to the digitized output data was used to determine the rms noise N from the result of subtracting the digitized data from the fitted sinewave data. The measurement errors are graphically shown in figure 3 in terms of the "effective number of bits." There were about seven effective bits over a frequency range of 1 kHz to 1 MHz and then the number dropped to about five bits at 10 MHz. The waveform storage option of the oscilloscope provides a resolution of 10 bits, and a perfect instrument would show a result of 10 effective bits in this test. The effective number of bits n is computed from

$$n = 10 - \log_2 \left(\frac{N}{Q/\sqrt{12}}\right) \; ,$$

where Q = 1 LSB, or it can also be computed from
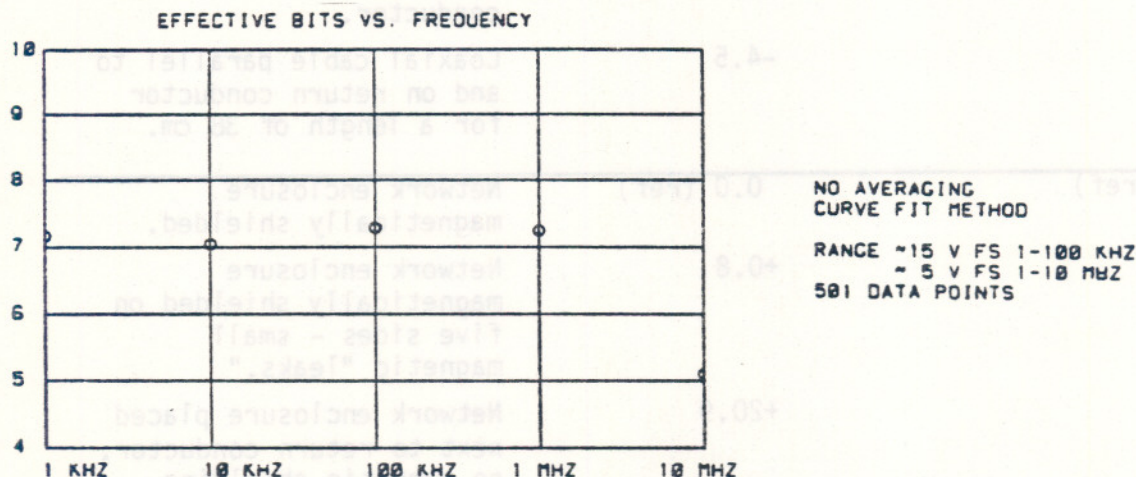
$$n = (S/N - 1.8)/6 \; .$$

Figure 3. Measurement results of the effective bits as a function of signal frequency (without averaging).

The noise N can be reduced by averaging each data point, which is easily done with the oscilloscope, and figure 4 shows the results for a 64-point average. Fast Fourier Transforms were applied to the output data to compute the

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S/N ratios for the 64-point averages. This method is computationally faster and gives substantially the same results as obtained using the curve fitting technique. Averaging (as was carried out here) improved the performance by one to two bits.

EFFECTIVE BITS VS. FREQUENCY

O -NO AVERAGING
☐ - 64/POINT

FFT METHOD
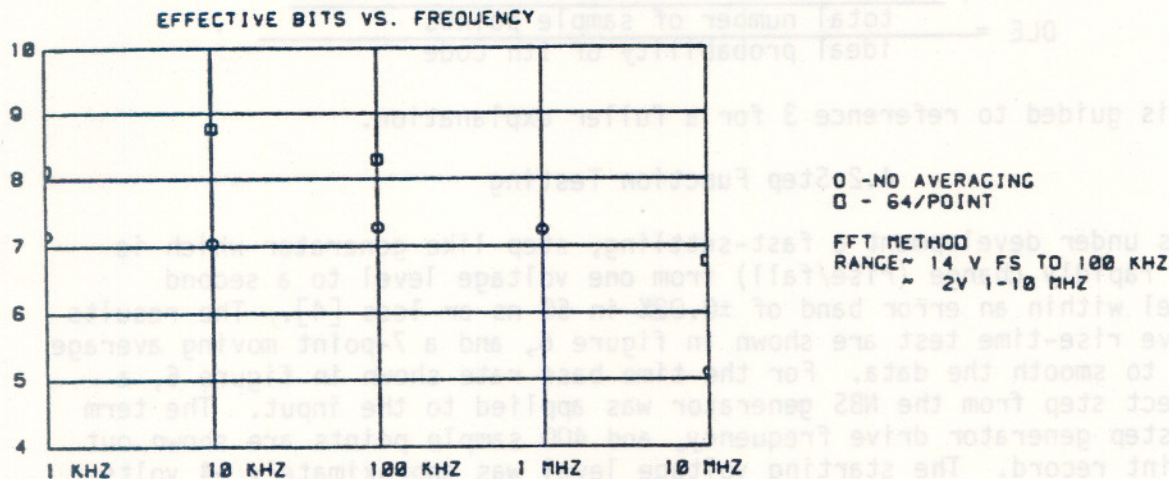RANGE~ 14 V FS TO 100 KHZ
~ 2V 1-10 MHZ

Figure 4.   Measurement results of the effective bits as a function of signal frequency (with averaging).

A differential linearity error test based on a sinewave input was also performed. Figure 5 shows a plot of the data obtained from this test. The number of sample points taken was 100,200 (one hundred thousand two hundred) and the test took several minutes to run. The statistical nature of this test gives a high confidence level of 99.9% that no code will exceed an error of 0.5 LSB. (An ideal digitizer has a quantization error of ±0.5 LSB.) Differential linearity errors at the end points (near codes 0 and 1023) should be disregarded since they are caused by a 5% overranging of the input signal. For the confidence level of 99.9%, there should be no more than 1 point out of the 1023 points exceeding ±0.5 LSB. However, as figure 5 shows, there are at least 16 points exceeding ±0.5 LSB.
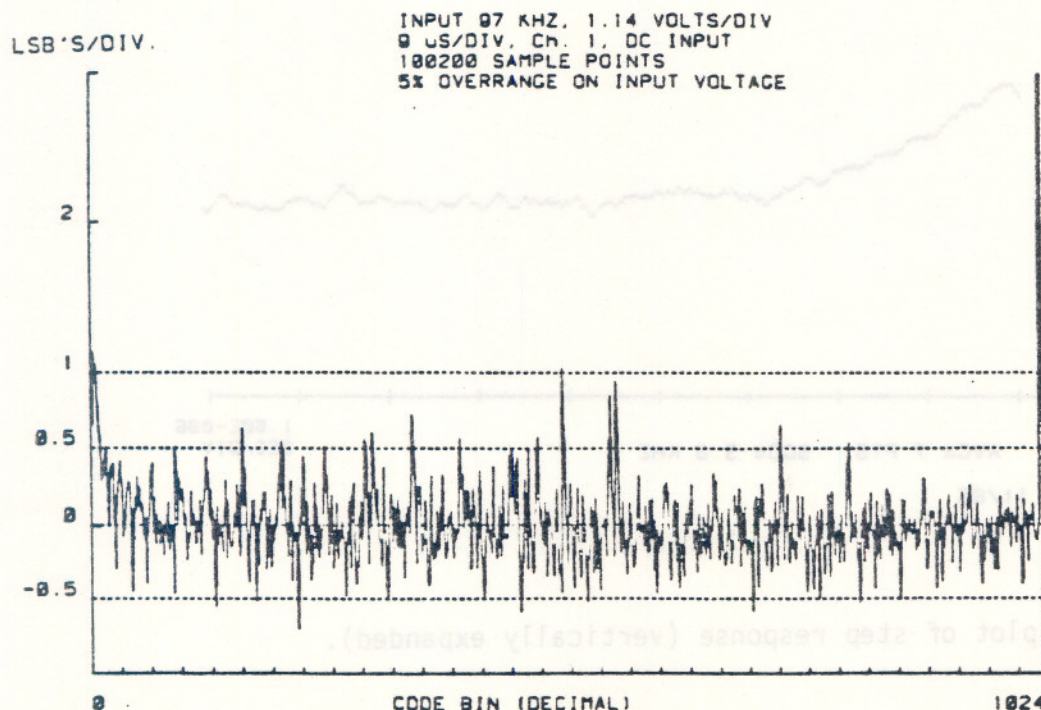
LSB'S/DIV.

INPUT 97 KHZ, 1.14 VOLTS/DIV
9 uS/DIV, Ch. 1, DC INPUT
100200 SAMPLE POINTS
5% OVERRANGE ON INPUT VOLTAGE

Figure 5.   Differential linearity error (in LSBs) versus code BIN (decimal).

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The computation of differential linearity error, as shown in figure 5, is determined by

$$DLE = \frac{\left(\dfrac{\text{actual number of occurrences of Ith code}}{\text{total number of sample points}}\right)}{\text{ideal probability of Ith code}}.$$

The reader is guided to reference 3 for a fuller explanation.

4.2 Step Function Testing

NBS has under development a fast-settling, step-like generator which is designed to rapidly change (rise/fall) from one voltage level to a second voltage level within an error band of ±0.02% in 50 ns or less [4]. The results of a positive rise-time test are shown in figure 6, and a 7-point moving average was applied to smooth the data. For the time base rate shown in figure 6, a nearly perfect step from the NBS generator was applied to the input. The term SGD is the step generator drive frequency, and 400 sample points are shown out of a 501-point record. The starting voltage level was approximately -4 volts, and the ending voltage level was approximately +4 volts. The ordinate of figure 6 is plotted in units of LSBs and is only a portion of the 0 to 1023-bit full-scale range which corresponds to 10 volts full-scale. The 8-volt step represents (8/10) x 1024 = 819 bits where only a small expanded portion is shown in figure 6. The approximate 20-bit overshoot out of the 819 bit change represents about 2.4% overshoot. The time required for the voltage to settle was about 5 μs.
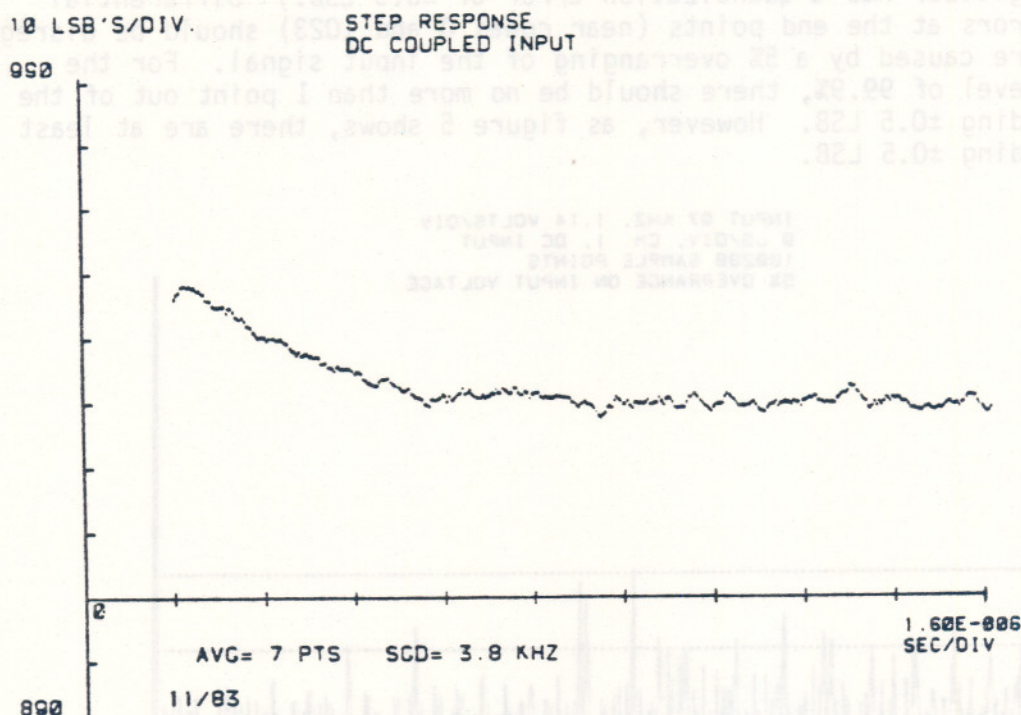

Figure 6. Analog plot of step response (vertically expanded).

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5. CONCLUSIONS

The measurement results suggest that high-pulsed currents can be measured by the coils tested with uncertainties of no less than a few percent unless extreme care is taken in calibration and subsequent use of these coils. Sensitivity changes due to positional orientation, proximity effects, differences from one coil to the next, and gap openings preclude precision measurements in the order of a few tenths of one percent. In all instances, the fixed coils are generally less sensitive to the effects of orientation and proximity than are the split coils. Rogowski coils can be made which are virtually insensitive to many of these types of effects, such as the coil used as a reference made by NBS.

The measurements made with the high-current shunt suggest that it is perhaps less sensitive to some of the same overall effects seen in the coil measurements. However, large errors can be introduced by improper placement or shielding of the potential lead from the shunt and the enclosure of the compensation network. Much more work would have to be done to completely qualify these and other effects at very high currents.

Test results from limited measurements made on the digital oscilloscope indicate performance within the manufacturer's specifications. Even so, this instrument will probably find limited use in the ultimate system for the calibration of very high current sensors. A sampling, multichannel device having better resolution will be required.

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The measurement of very high ac currents presents special problems in the selection of current sensors, instrumentation, and techniques. This report discusses initial test results for Rogowski coils and high-capacity current shunts often used to measure large ac currents. Eight Rogowski coils of three sizes and ratings were tested at a nominal current of 1000 A. The coils were compared against an NBS precision air-core mutual inductor to obtain a measure of complex sensitivity, positional sensitivity, gap-separation sensitivity (for the split-coil types), and proximity effects of the return conductor and of ferromagnetic material. The shunt was tested to assess the proximity effects of the return conductor and of ferromagnetic material. It was concluded that the particular Rogowski coils tested would not have measurement uncertainties of less than a few percent unless extreme care was taken in their calibration and subsequent use. The measurements for the shunt suggest somewhat less proximity effect than those for the coils. A digital oscilloscope was evaluated for possible use as a transient recorder. The effective number of bits, the differential linearity, and the response to a step function were determined.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

ac current measurement; calibration; current shunts; digital oscilloscope; high current; Rogowski coils.

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