NBSIR 83-2666

Effects of High-Voltage Switching on the EPRI-NBS Coupling Capacitor Voltage Transformer (CCVT) Calibration System Standard Divider

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

March 1983

Sponsored in part by:
Electric Power Research Institute
Palo Alto, California 94304

NBSIR 83-2666

EFFECTS OF HIGH-VOLTAGE SWITCHING ON THE EPRI-NBS COUPLING CAPACITOR VOLTAGE TRANSFORMER (CCVT) CALIBRATION SYSTEM STANDARD DIVIDER

David L. Hillhouse

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

March 1983

Sponsored in part by:
Electric Power Research Institute
Palo Alto, California 94304

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (cont.)

EFFECTS OF HIGH-VOLTAGE SWITCHING ON THE EPRI-NBS COUPLING CAPACITOR VOLTAGE TRANSFORMER (CCVT) CALIBRATION SYSTEM STANDARD DIVIDER

David L. Hillhouse

Abstract

This report presents the results of tests of the effects of high-voltage switching on the EPRI-NBS CCVT calibration system's capacitive standard divider, completing an investigation stemming from the results of three calibrations at a Gulf States Utilities substation.

Initial tests consisted of full-scale (300 kV) switching operations at EPRI's Waltz Mill test facility, during which the divider exhibited significant ratio offsets (average = +0.2%, maximum = nearly +0.5%). Tests were continued at the National Bureau of Standards (NBS), where it was determined that operation of a grounding switch, installed to protect the divider low side during high-voltage switching, caused ratio offset by trapping charge on the divider's low side capacitor. This resulted in residual dc voltage which changed the value of the divider's low-side capacitance. The addition of a bleeder resistor eliminated the problem in the laboratory. With the bleeder resistor in place, the Waltz Mill tests were repeated. Fifty high-voltage switching operations indicated a negligible shot-to-shot variation (average = -1ppm, σ = 80 ppm).

No obvious correlation was found between the ratio offsets described above and the results of CCVT calibrations performed while the effect may have been present in the divider. Experience indicates that a significant proportion of calibrated CCVTs is outside metering tolerance. Long-term simultaneous monitoring of a sizeable number of CCVTs is suggested.

Key words: calibration; capacitive divider; CCVT; error sources; high-voltage measurements; high-voltage switching; ratio offset; trapped charge; Waltz Mill tests.

1. INTRODUCTION

The work reported here represents the completion of an investigation, co-sponsored by the Electric Power Research Institute (EPRI), into some unexplained results obtained from three calibrations at a Gulf States Utilities (GSU) substation [1].[1] These results consisted of changes in ratio and phase angle between the first two sets of calibration values which seemed to be correlated by phase, i.e., most of the devices on a given phase shifted in the same general direction and by similar amounts. Seeking to clarify this, the third set of measurements was undertaken.

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

Analysis of the three sets of data produced some evidence of a bias voltage in the 1979 data. Investigation of all plausible known sources of error in the NBS system, the substation, and the CCVTs themselves failed to produce a probable source for such a bias voltage. The analysis did suggest the possibility that high-voltage switching[2] might affect the divider ratio.

Since the NBS laboratories do not have the capability to perform full-voltage switching on the 500 kV (300 kV to neutral) divider, such tests were done at the EPRI Waltz Mill Underground Transmission Test Facility, Ruffs Dale, PA. The initial tests, in October 1981, were followed up with further tests at NBS and a return to Waltz Mill in April 1982.

2. FIRST WALTZ MILL TESTS

2.1 Waltz Mill Facility

A simplified circuit diagram [2] of the Waltz Mill facility is shown in figure 1. Briefly, this facility can supply 60 Hz voltage to 1100 kV, in a step-up from utility-furnished 138 kV. The 1100 kV bus contains motor-driven disconnect switches, allowing simulation of the switching environment encountered by the standard divider in an operating substation. Voltage ratios can be measured very accurately using a 1500 kV compressed gas standard capacitor which is connected permanently to the 1100 kV bus. The voltage can also be monitored via an 1100 kV CCVT.

2.2 General Test Procedure and Circuits

The high-voltage switching test measurement procedure consisted of the following principal steps:

Step 1. Calibration of the Waltz Mill 1500 kV compressed gas standard capacitor, C_{SW} (fig. 2), using NBS Standard Capacitor, C_{ST}, and the current comparator bridge;

Step 2. Measurement of the standard divider ratio, ρ_{SD}, using C_{SW} and the current comparator bridge (fig. 3);

Step 3. Repeat of step 2 to obtain the Waltz Mill 1100 kV CCVT ratio, ρ_C (fig. 4); and

Step 4. Comparison of the standard divider and CCVT ratios using the simplified system voltage comparator [3-5] to cross check steps 2 and 3 (fig. 5).

The four steps are related in the following manner. Step 1 establishes C_{SW} as the on-line reference for the bus voltage. Step 2 measures ρ_{SD} directly, using accurately known standards C_{SM} and C_{SW}. Step 3 obtains the ratio ρ_C of the monitoring CCVT in the same manner, and step 4 compares ρ_C

---

[2]Closing a motor-driven disconnect switch in order to connect the divider to the 500 kV bus or opening it to disconnect the divider from the bus.

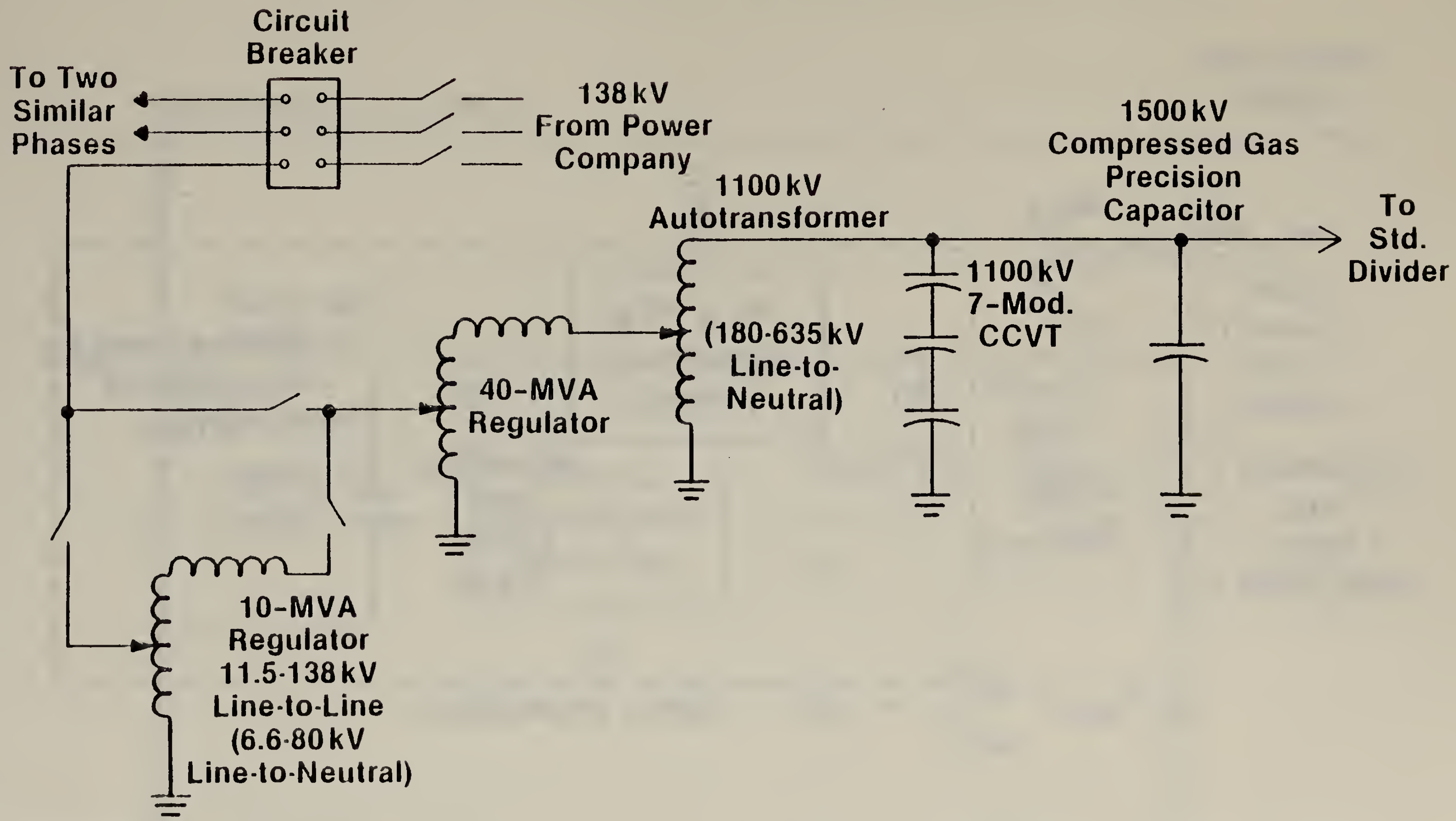


Figure 1. Simplified diagram of the Waltz Mill EHV-UHV test circuit

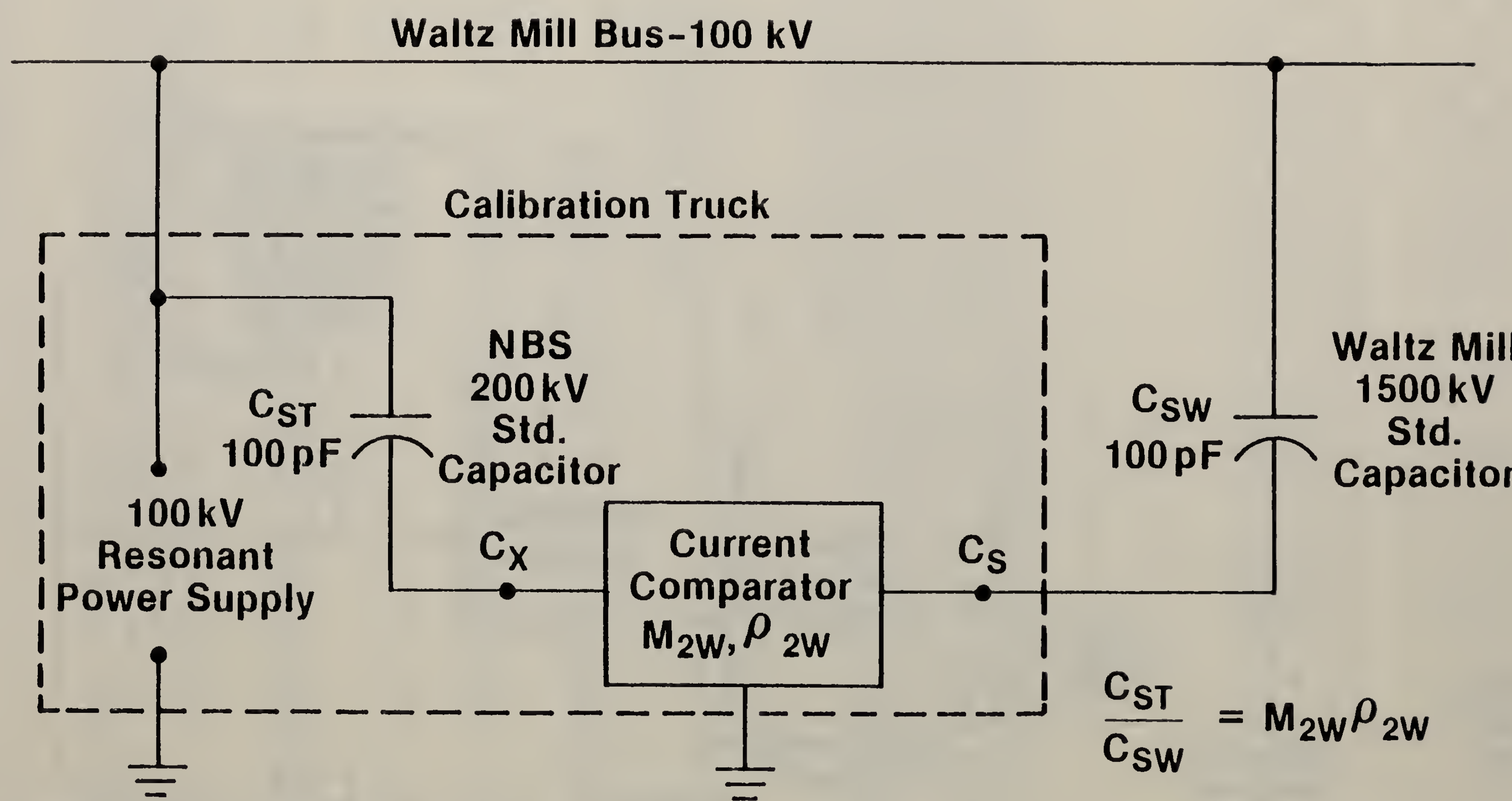
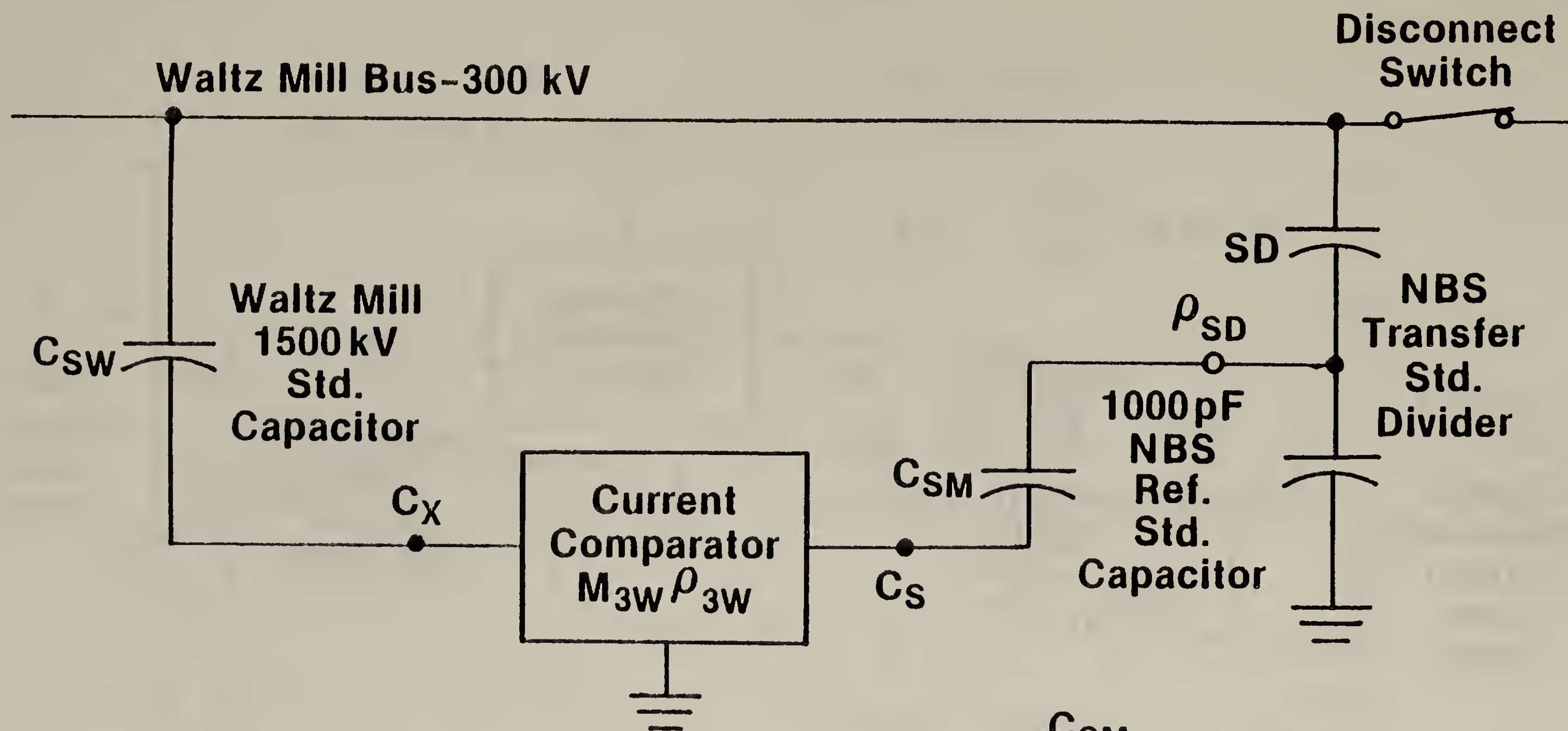


Figure 2. Step 1, calibration of Waltz Mill 1500 kV compressed gas standard capacitor, C_{SW}



$$\rho_{SD} = \frac{C_{SM}}{C_{SW}} M_{3W}\rho_{3W}$$

Figure 3. Step 2, measurement of the NBS standard divider ratio, ρSD, using the results of step 1

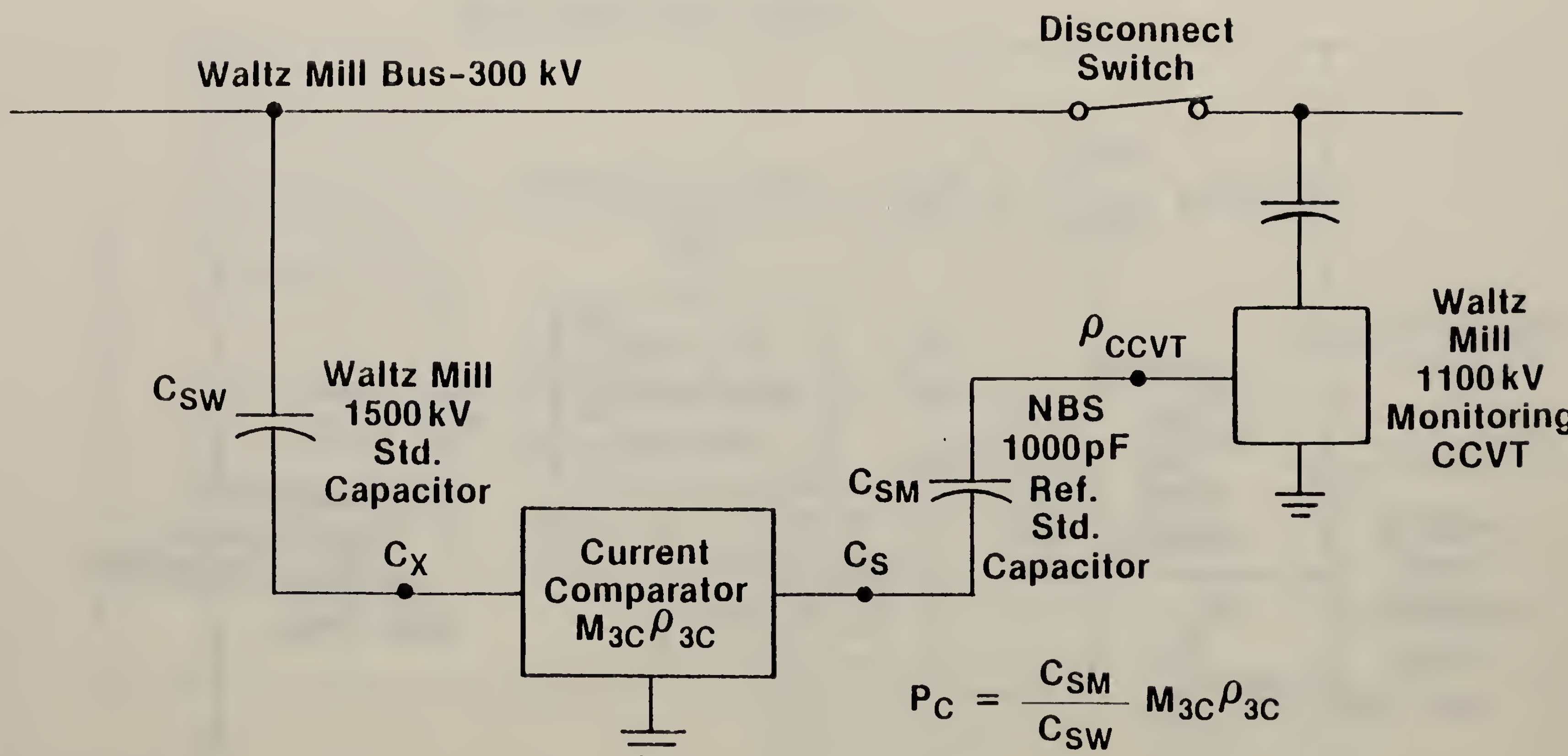


Figure 4. Step 3, measurement of the Waltz Mill 1100 kV monitoring CCVT ratio, ρ_C, using the results of step 1

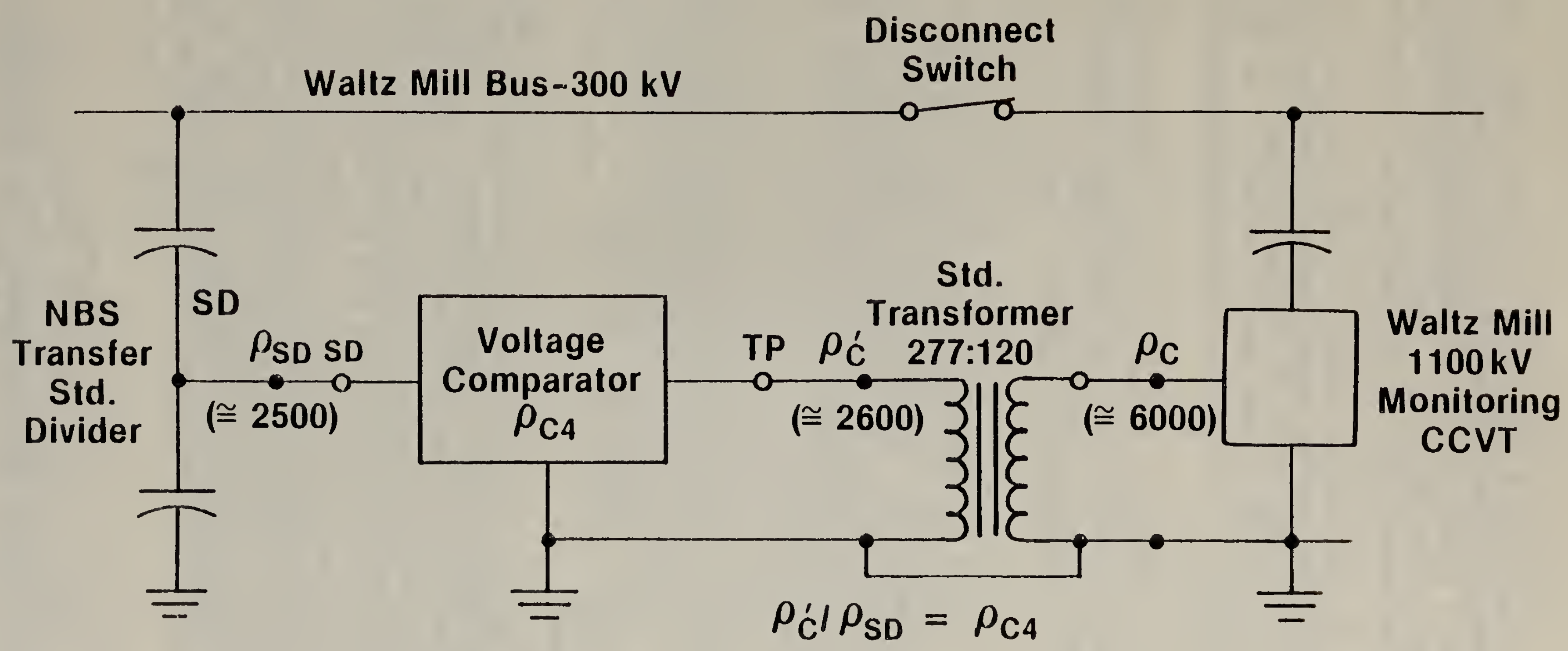


Figure 5. Step 4, comparison of the NBS standard divider ratio and the Waltz Mill monitoring CCVT ratio, using the simplified system's voltage comparator

and ρ_{SD}. Combining steps 3 and 4 yields ρ_{SD} indirectly. This indirect value should agree with the direct value from step 2. Combining this with the repetition of step 2 at the end of the sequence keeps the entire measurement in control by forming a closed set, i.e., steps 2, 3, 4, 2. The complete set was obtained initially, and after most disconnect switch operations.

In step 1 (fig. 2), the current comparator reads the ratio $C_{ST}/C_{SW} = M_{2W}/\rho_{2W}$. The value of C_{ST}, determined earlier in an identical comparison with a low voltage reference standard (C_{SM} = 1000.00 pF), is then used to calculate C_{SW}. The value of C_{SW} (103.155 pF) was determined twice -- at the beginning of the five days of tests and at the end. The two values agreed to within 50 ppm (parts per million).

In step 2 (fig. 3), standard divider ratio ρ_{SD} is determined directly from the current comparator multiplier and ratio product readout ($M_{3W}\rho_{3W}$) and the previously known value of C_{SM} and C_{SW}. In step 3 (fig. 4), the ratio ρ_C of the CCVT is determined in an identical manner.

In step 4 (fig. 5), the voltage comparator reads out $\rho_C'/\rho_{SD} = \rho_{C4}$ where ρ_C' is the CCVT ratio ρ_C, modified by the ratio of the 120:277 low-voltage standard transformer (precisely, by 0.43344), and ρ_{C4} is the ratio setting of the comparator. From this the indicated ratio of the divider can be computed as $0.43344\rho_C/\rho_{C4}$. The standard transformer is required in order to bring the nominal 6000:1 ratio of the CCVT to within the range (1.11111:1) of the voltage comparator. For full discussion of this limit on the voltage comparator, see [5].

The usual procedures for a field calibration were followed, i.e., the divider was calibrated in the NBS laboratory at 100 kV, and re-calibrated at 100 kV upon arrival at the site, using the power supply aboard the truck [4]. This calibration was repeated during the week, at the end of the tests, and again afterward in the NBS laboratories. The spread of all of these values was approximately ±0.02% from the initial Waltz Mill value, which was taken as arbitrary reference.

A change in divider ratio attributable to high-voltage switching was considered to be improbable for the following reasons: (1) field calibration of highly accurate inductive voltage transformers (VTs) had agreed with NBS calibration of the same devices in the factory to about 0.01% ([3], p. 8-15); (2) in a calibration at another substation shortly before the third GSU tests, NBS results for two CCVTs recently returned from the factory agreed with factory calibration results to within ±0.02%. In order to obtain a reasonable estimate of the limiting probability of the occurrence of a high-voltage switching effect within the limits of available testing time, up to 50 switching operations were planned. It can be shown that 50 tries with no occurrence of an event indicate a 99.5% confidence[3] that the event occurs at most one time in 10, and an 82% confidence that it occurs at most one time in 30.

[3] $P' = 1-(1-P)^n$, where P' is the above percentage, P is the probability of occurrence guarded against, and n is the number of operations.

2.3 Detailed Test Procedure

After the preliminary calibrations alluded to earlier, the following switching procedure was planned:

1. Close the divider low-side grounding switch S3, to protect the auxiliary divider (see fig. 6, and discussion below);

2. Turn on the Waltz Mill power, raise voltage to 300 kV (500 kV line-to-line);

3. Open grounding switch S3;

4. Obtain a reference value of ρ_{SD}, via steps 2 through 4 (sec. 2.2);

5. Close grounding switch S3;

6. Open, then close, the motor-driven disconnect switch on the 300 kV line; and

7. Repeat (3) through (6) above, up to 50 times.

The function of grounding switch S3 in (1), (3), and (5) above will be discussed here, since it is a key element in this investigation, as will be seen later. Refer to figure 6, which shows the basic circuit of the divider. The purpose of S3 is to protect the auxiliary divider from surge voltages while the divider is being connected to or disconnected from the high-voltage bus. When S3 is closed, it completes a low-inductance path around the low side of the standard divider via a copper strap 40 mm wide by 2 mm thick. This configuration was incorporated into the system in 1979, after some auxiliary divider capacitors were damaged during switching.

2.4 Test Results

Contrary to expectations, some divider ratio offset was produced with nearly every high-voltage switching operation. These offsets ranged up to 0.32%. After a number of such switching operations on the three-module divider at 300 kV, other tests were performed. These included switching at lower voltages, switching of single-module dividers at 100 kV, and operation of the low-side grounding switch (S3, fig. 6) with the divider remaining energized at 300 kV. Ratio shifts were found under all the conditions listed above.

A summary of these results at 300 kV is shown in table 1, both for high-voltage switching (which includes grounding switch operation) and for grounding switch operation only, together with average values and average (+) and (-) values. Note that two-thirds of the values, including almost all of those greater than 0.1%, are (+). The data taken at Waltz Mill did not reveal the source of this effect, so further investigation was undertaken later at NBS.

As reported earlier, the before-and-after measurements of C_{SW}, the Waltz Mill 1500 kV standard capacitor, agreed to within 50 ppm. In addition, the divider ratio ρ_{SD}, as obtained directly via measurement step 2, was compared with the indirect value obtained via steps 3 and 4 for

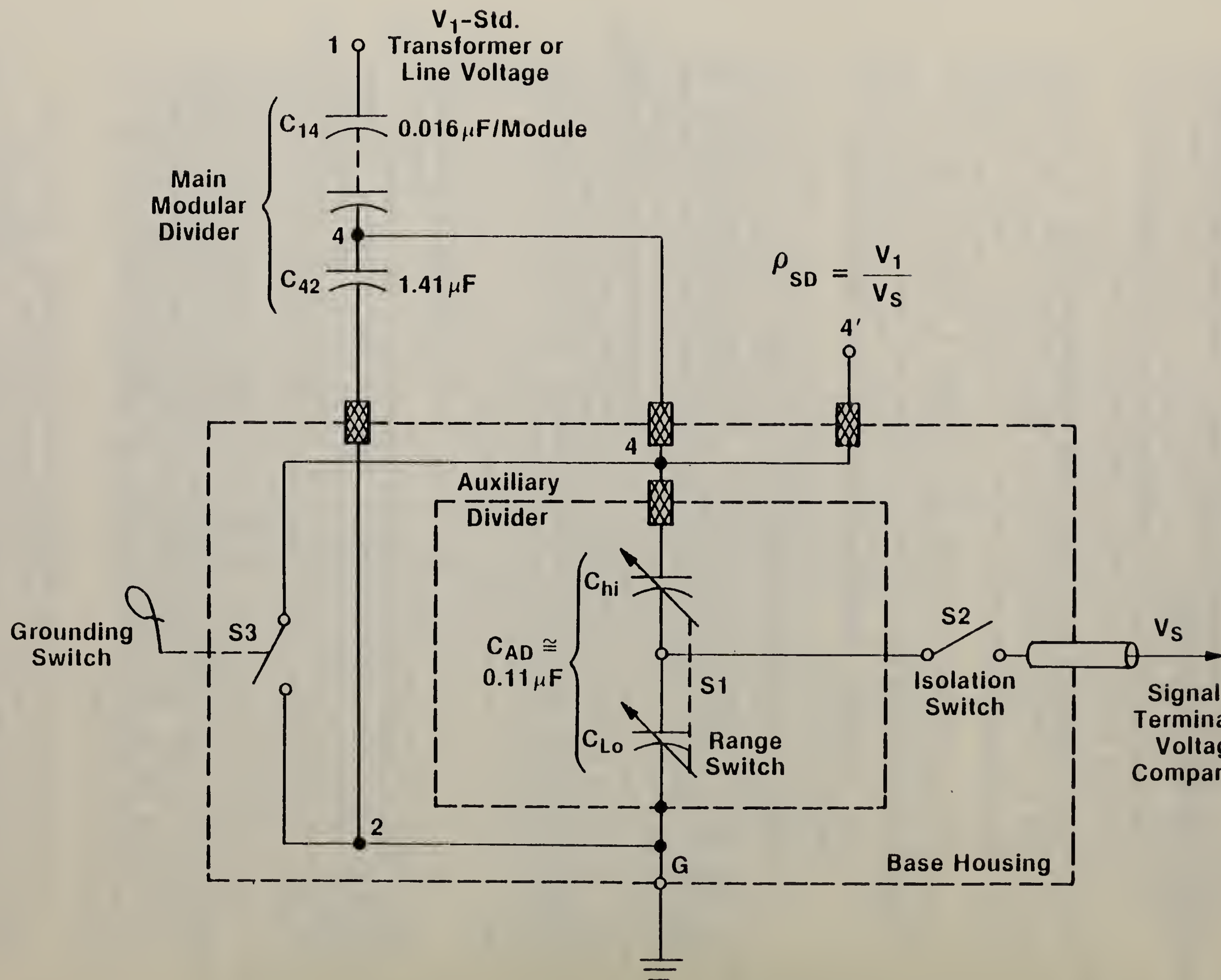


Figure 6. Basic circuit of the NBS capacitive standard divider

about 20 data points. The two sets of values agreed to about 0.01%, with a standard deviation of about ±0.02%. This indicates that the Waltz Mill measurements were probably under control to better than 0.06% (three standard deviations).

3. NBS TESTS

Available voltage and space limited NBS testing to 50 kV on a one-module divider for high-voltage switching simulating the substation disconnect switch, and to 100 kV for grounding switch operation. This represented 50% and 100% of rated voltage stress, respectively. However, the Waltz Mill results indicated that these stress levels were high enough to produce the unexplained ratio effects. This permitted laboratory investigation of the high-voltage switching effect instead of far more expensive and inconvenient full-scale field tests at Waltz Mill.

3.1 Grounding Switch Operation

3.1.1 Discussion of Tests

Because a correlation between grounding switch operation and divider ratio offset was evident at Waltz Mill (table 1), a peculiar surge behavior of the divider low side (fig. 6) was suspected, either in capacitor C_{42} or in the auxiliary divider. The test circuit for investigating this is shown in figure 7. The procedure consisted of applying 100 kV, balancing the current comparator, closing grounding switch S3 for a few seconds, opening S3, then rebalancing the current comparator and measuring any change, $\Delta\rho_{SD}$, in ρ_{SD}.

As at Waltz Mill, almost every grounding switch operation produced a significant ratio offset. After approximately 20 operations, the auxiliary divider was disconnected at terminal 4' (see fig. 7), and low-voltage standard C_{SM} replaced with 20 kV standard C_J, as shown dotted on the figure. The effect was unchanged, indicating that the problem was not in the auxiliary divider.

At this time, a residual dc voltage was discovered on C_{42} after completing a measurement. A different dc voltage, associated with a different divider ratio offset, was then found each time.[4] Removing the dc voltage by discharging C_{42} removed the ratio offset. Thus it became evident that a major cause of divider ratio offset was simply the voltage dependence of the capacitance of C_{42}.

The mechanism for charge trapping, resulting in the residual voltage above, can be explained by reference to figure 7. If switch S3 is opened while ac voltage is applied to the divider, whatever voltage is present on C_{42} when the switching arc is extinguished remains there, subject to available discharge paths. Since these paths are all capacitive, even with terminal 1 safety-grounded, the voltage can decay only through the very high leakage

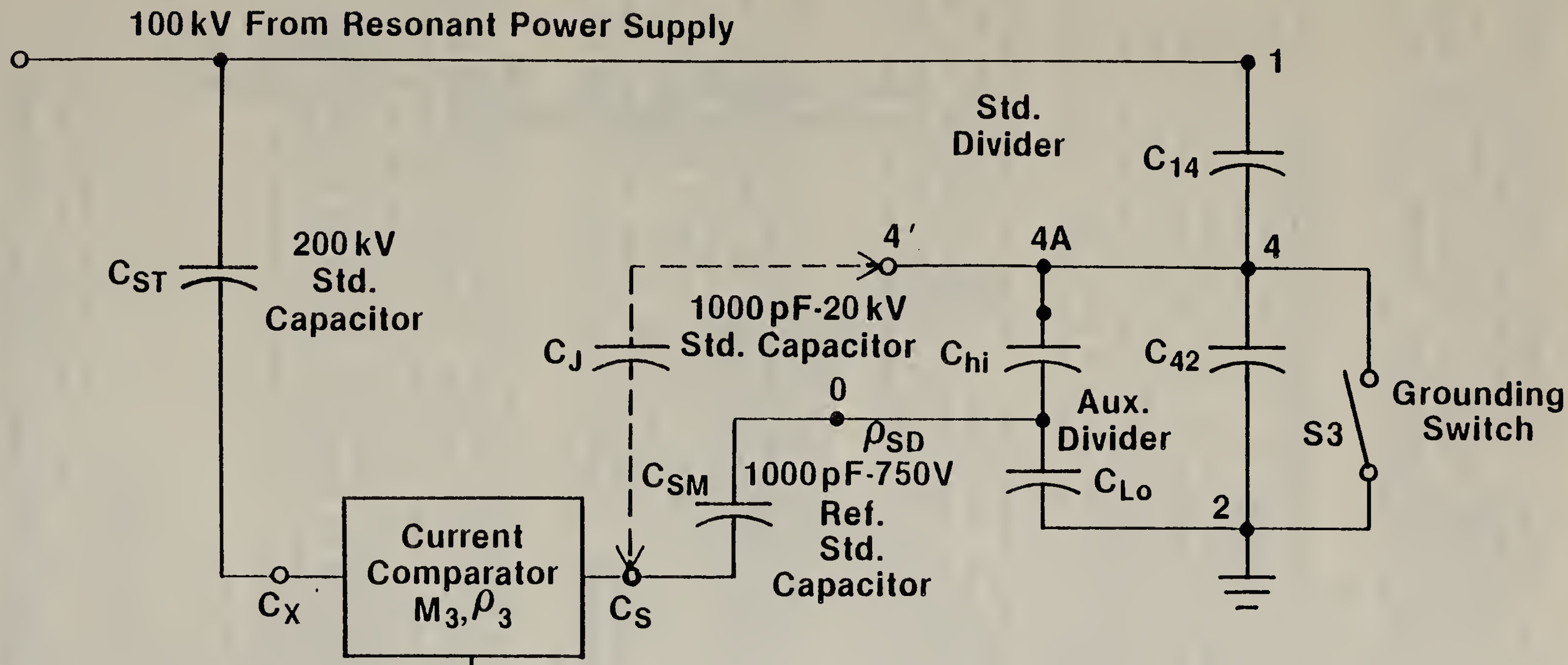
---

[4] This ratio offset was always positive, although both positive and negative voltages were found.

Table 1. Standard divider ratio deviation due to high-voltage switching, first Waltz Mill tests (V = 300 kV)

Disconnect switch operation		Grounding switch operation, only	
Operation No.	$\Delta\rho_{SD}/\rho_{SD}$ (percent)	Operation No.	$\Delta\rho_{SD}/\rho_{SD}$ (percent)
1	0.18	1	0.20
2	0.20	2	0.19
3	0.06	3	0.26
4	0.06	4	0.20
5	-0.06	5	0.16
6	0.21	6	-0.01
7	-0.06	7	-0.02
8	0.23	8	0.11
9	-0.07	9	0.19
10	0.20	10	0.08
11	-0.02	11	0.16
12	-0.13	12	0.30
13	0.32	13	0.22
14	0.10	14	0.27
15	-0.08	15	0.10
16	-0.04	16	-0.07
17	0.13		
Average	0.08		0.15
Average (+)	0.17		0.19
Average (-)	-0.07		-0.03

Overall Average	0.11
Overall Average (+)	0.18
Overall Average (-)	-0.06



$$\rho_{SD} = \left(\frac{C_{ST}}{C_{SM}}\right) M_3\rho_3, \text{ or } \rho'_{SD} = \left(\frac{C_{ST}}{C_J}\right) M'_3\rho'_3$$

Figure 7. Circuit for NBS grounding switch operation tests of one-module standard divider

resistances of these paths. This was confirmed by leaving the trapped dc voltage on and tracking its decay. An equivalent time constant of the order of three days was found. The decay was not a simple exponential, but was considerably faster during the first few hours (equivalent $\tau \cong 25$ hours). This suggests a nonlinear, perhaps voltage-dependent, leakage resistance. A time constant of three days implies a leakage resistance of about $1.7 \times 10^{11}\ \Omega$, and of 25 hours, about $6 \times 10^{10}\ \Omega$.

In order to relate the above observations to the Waltz Mill tests, refer to section 2.3. Note that the Waltz Mill routine (identical in this respect to the routine followed in a regular CCVT field calibration) always included opening the grounding switch with voltage on the divider. Therefore, trapped charge would be expected each time the divider was connected to the high-voltage bus. This appears to explain, at least qualitatively, the Waltz Mill results. Furthermore, since the grounding switch is always closed before removing the divider from the line during any full-voltage test, this voltage is always removed and would therefore never be found during normal substation testing.

In relating the measured dc voltages to the ac voltage applied to C_{42}, a purely capacitive circuit was postulated. It can be shown that in such a network the residual dc voltage should equal the peak value of the interrupted ac wave. A few data points sufficed to show that this voltage was distributed all the way from essentially zero to the peak value (as table 1 already implies).

In order to obtain the distribution and average value of this residual voltage, 150 grounding switch operations were performed at 100 kV on a one-module divider, for which voltage stress was the same as at 300 kV on the full divider. Figure 8 shows a histogram of the magnitude of the residual dc voltage for these tests. The mean is 910 V, or about 89% of the average value of the ac voltage (1020 V) applied to C_{42} at 100 kV on the divider.[5] If the dc voltage were randomly distributed, its mean value would equal the average value of the sine wave. Therefore, the residual voltage does not appear to be truly randomly distributed.

A smaller number of grounding switch operations (51 values) was performed on a very similar one-module divider manufactured by a different company. A histogram of the magnitude of the residual dc voltage for this divider is shown in figure 9. The mean value is higher and closer to that for the average value of a sine wave. The distribution is considerably different also, with a significantly larger proportion of values near the peak. Since the purpose of these tests was to verify the existence of the effect and to delineate it, not to investigate the physics of it, the reasons for the unexpected distributions and for the differences between the two modules were not investigated.

---

[5] ρ_{SD} for a one-module divider $\cong 88$,
so that V_{peak} is approximately $(10^5/88)\sqrt{2} \cong 1610$ V.
$V_{avg} = (2/\pi)V_{peak} \cong 1020$ V.

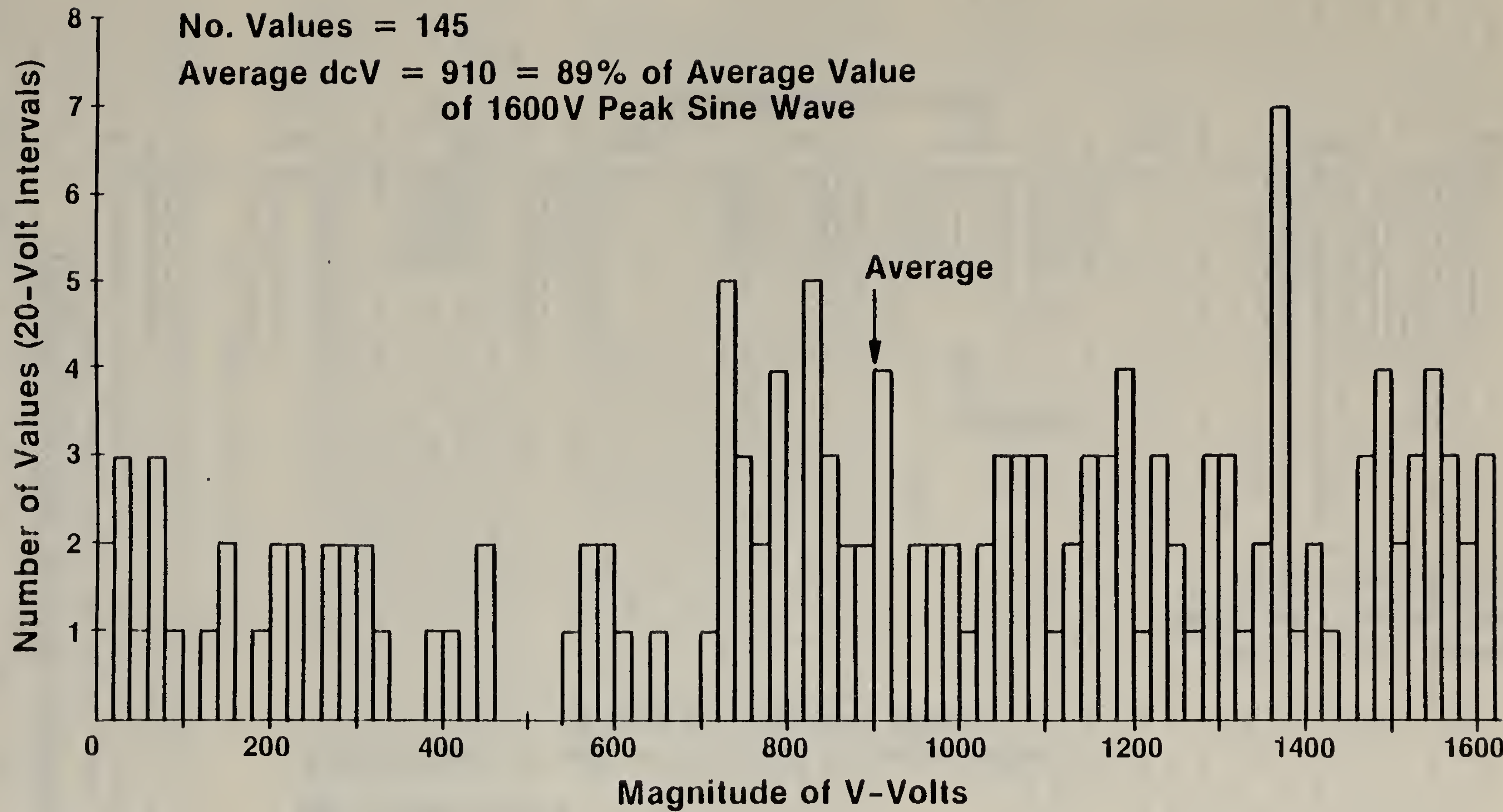


Figure 8. Trapped dc voltage histogram, one-module divider

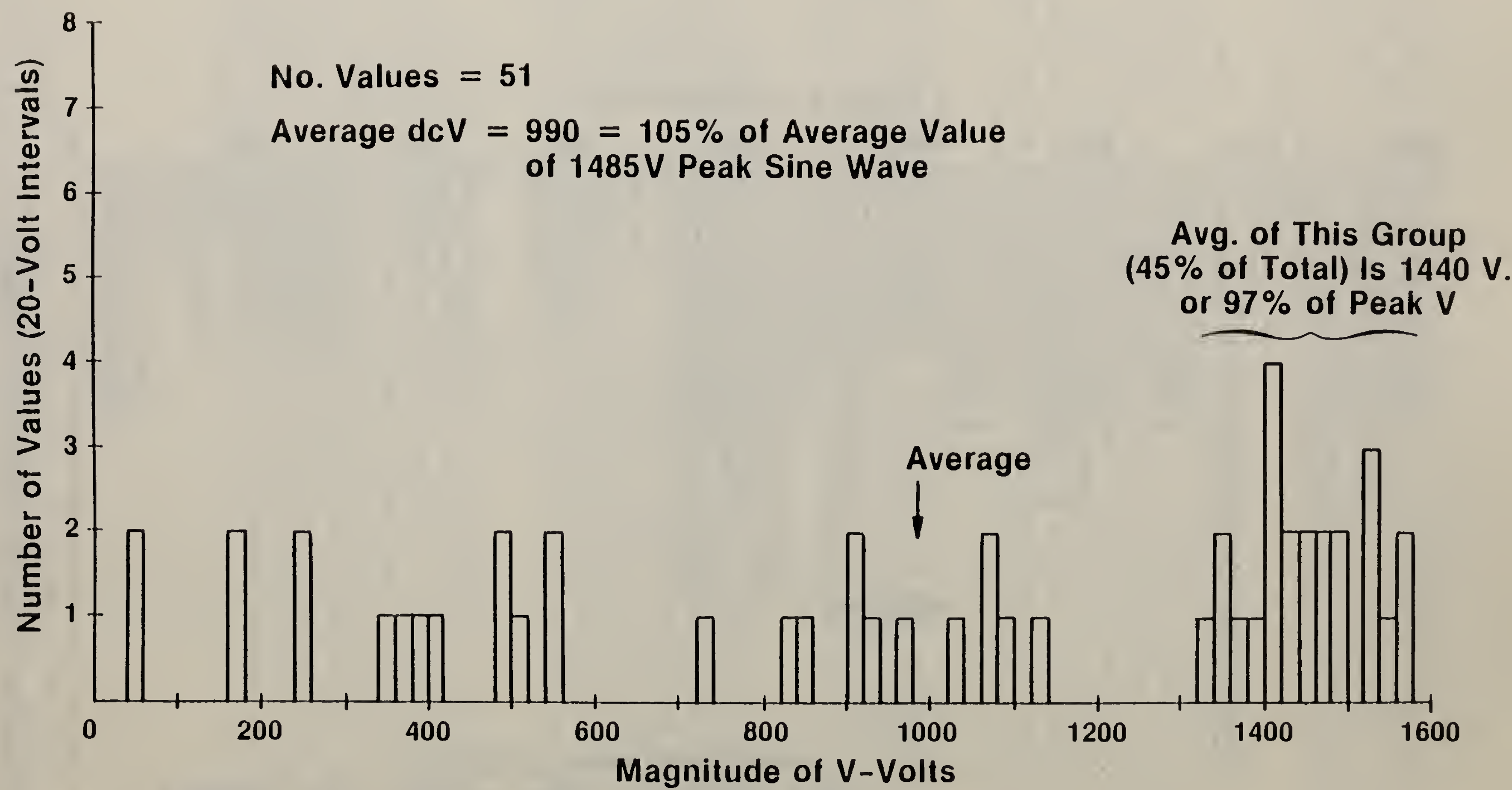


Figure 9. Trapped dc voltage histogram, one-module divider, second manufacturer

In addition to the grounding switch operations, ratio offset was also affected by applying positive and negative dc voltages with a dc power supply, and ac voltage up to the highest dc voltage trapped during the grounding switch operations (≅1600 V rms). The results are summarized in figure 10, which shows power curves, $\Delta\rho_{SD}/\rho_{SD} = aV^b$, fitted to the data. Both the dc and ac voltage data formed very smooth curves, as their R^2 (coefficient of determination) values indicate. For a perfect fit, $R^2 = 1$. Greater scatter was present in the grounding switch operation data, as reflected in the smaller R^2 value, but even here the maximum scatter of $\Delta\rho_{SD}/\rho_{SD}$ was less than ±0.05% from the fitted curve. Most important, note that the power coefficient b equals approximately two in all cases. This conforms to the square-law increase in capacitance expected due to decrease in the distance between the plates under the action of electrostatic forces, when the capacitor is operating well above resonance [6]. For this case, $C = C_0 (1 + aV^2)$, in which C_0 is the capacitance at zero voltage, and aV^2 corresponds to aV^b above, with $b = 2$. Since all CCVT capacitors are of paper-oil-foil construction, they form non-rigid mechanical systems, whose resonant frequency should be well below 60 Hz. The corresponding curves for the other manufacturer's one-module divider were almost identical to those in figure 10.

3.1.2 Summary

Figure 10 indicates that ratio errors approaching +0.5% (there are no negative errors) can be introduced into the standard divider at 500 kV by the operation of the grounding switch. Figure 11 shows a histogram for $\Delta\rho_{SD}/\rho_{SD}$ comparable to that shown for voltage in figure 8. The tabulation on figure 11 shows a generally decreasing distribution as the ratio offset increases. If this distribution holds in the field, the probable offset is approximately 0.17%. The probability of either very large (>0.4%) or very small (<0.05%) offsets is relatively small. Since at least three switching operations are performed during a CCVT calibration series (one per phase), it seems to be highly probable that an offset at least equal to 0.17% would be introduced at least once per calibration ($p = 1-0.5^3 = 0.875$).

After completing the grounding switch operation tests, it was believed that trapped charge was the major cause for the ratio offsets seen at Waltz Mill. However, some doubt remained because of some unexplained data. Note from table 1 that ten negative values were obtained. It can be argued plausibly that those smaller than -0.06% (four values) are within measurement uncertainty. The other six values, particularly disconnect switch operations Nos. 12 and 15, remain. They suggest the possibility that some other mechanism also operates during high-voltage switching. This was investigated, as described below.

3.2 High-Voltage Switching

As indicated earlier, available voltage and space allowed high-voltage switching to be performed only up to 50 kV, on a one-module divider. This is only half the voltage stress encountered in a 500 kV CCVT field calibration. The test circuit for high-voltage switching was the same as for the grounding switch operations (fig. 7), with dotted capacitor C_J in place, the auxiliary divider disconnected, and the resonant power supply replaced by a testing transformer. The disconnect switch consisted of a hinged aluminum rod extending from the transformer corona ring to the divider corona ring.

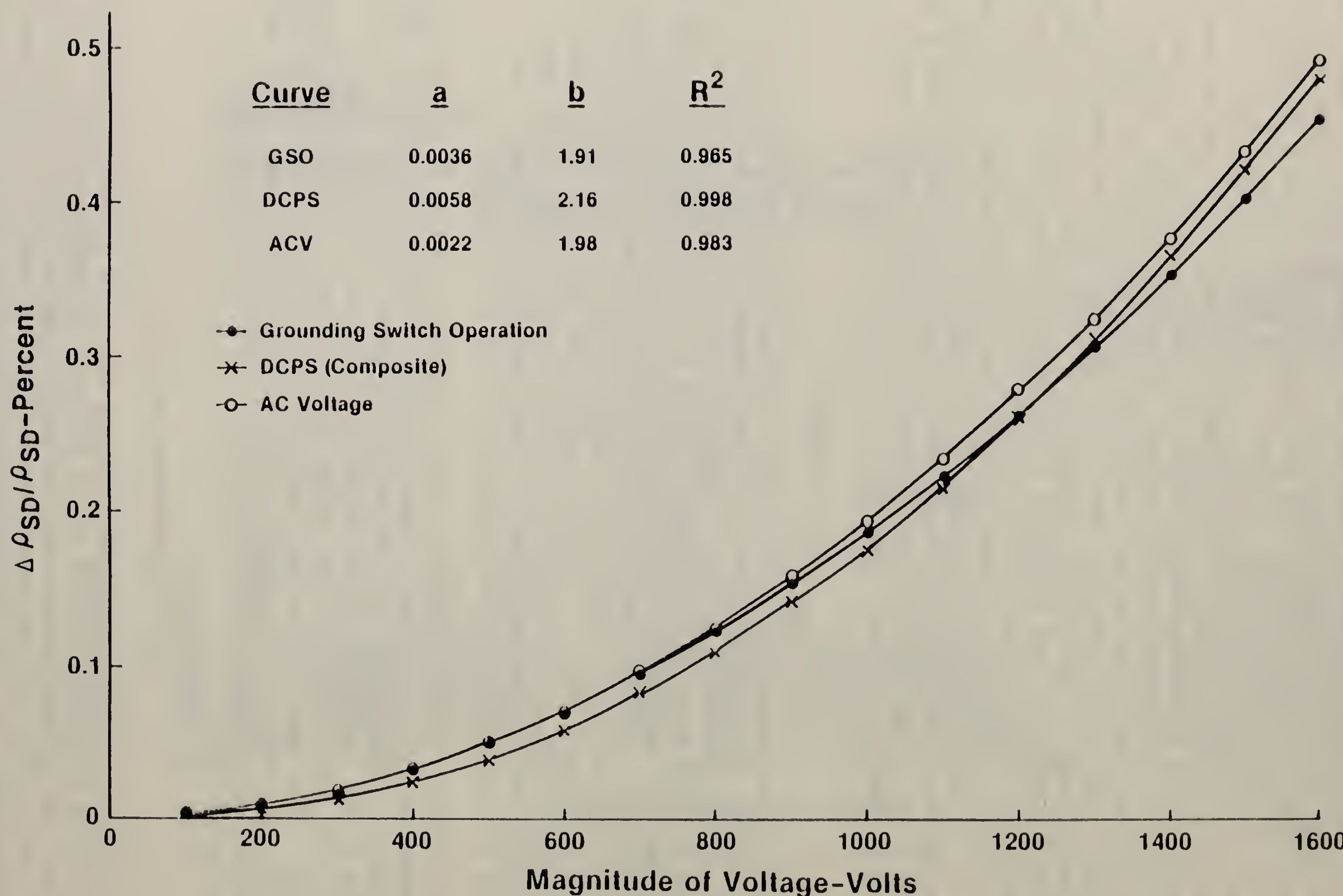
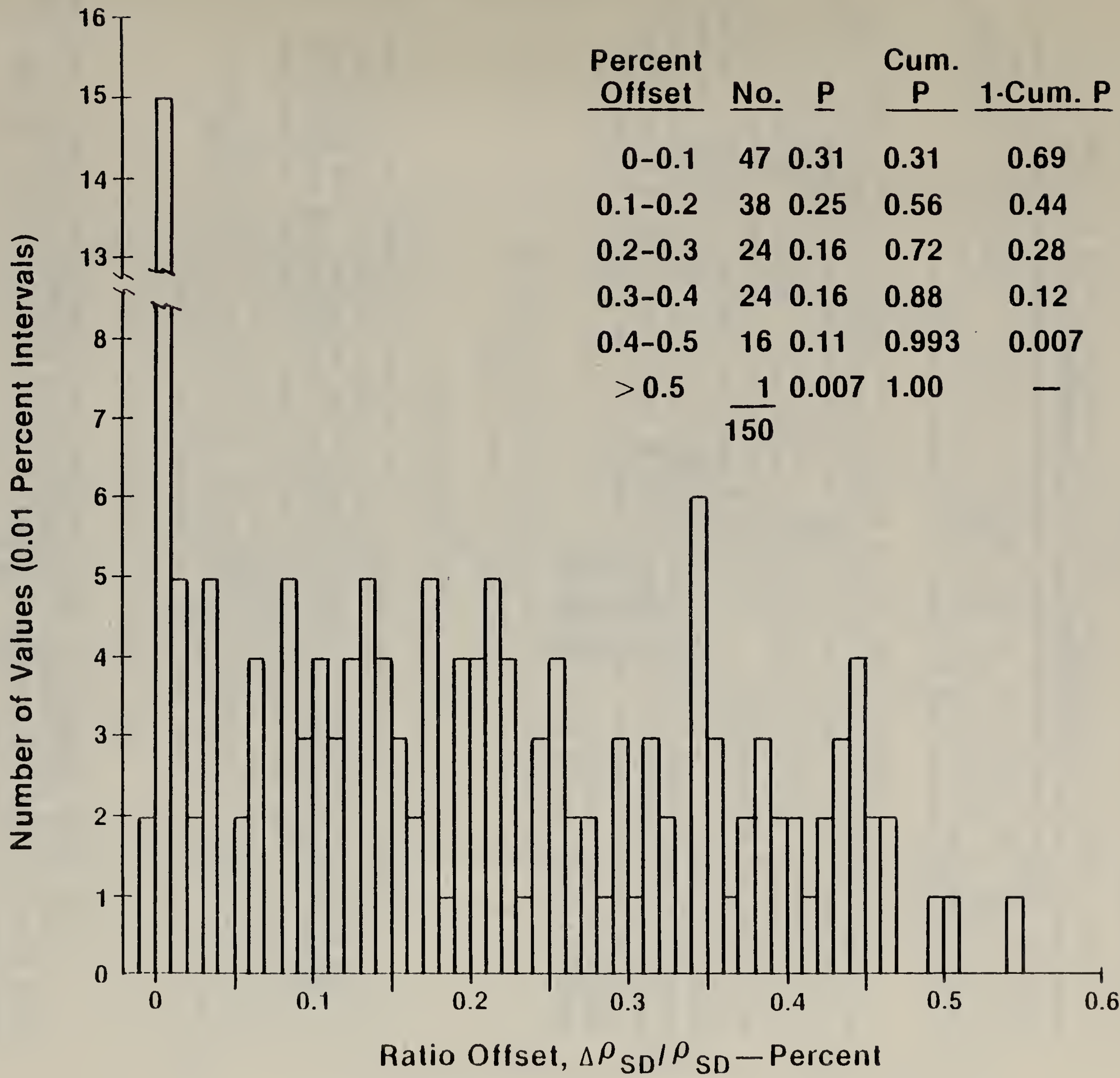


Figure 10. Standard divider ratio offset for dc voltage (1) trapped by grounding switch operation; (2) applied by dc power supply; and (3) for ac voltage applied to low-side capacitor C_{42} (regression fit, power curve, $\Delta\rho_{SD}/\rho_{SD} = aV^b$)



Percent Offset	No.	P	Cum. P	1-Cum. P
0–0.1	47	0.31	0.31	0.69
0.1–0.2	38	0.25	0.56	0.44
0.2–0.3	24	0.16	0.72	0.28
0.3–0.4	24	0.16	0.88	0.12
0.4–0.5	16	0.11	0.993	0.007
>0.5	1	0.007	1.00	—
	150			

Figure 11. Ratio offset histogram, one-module divider

The switch was operated manually by a rope-and-pulley arrangement. In a procedure similar to that at Waltz Mill, the divider ratio was measured, the disconnect switch opened for a few seconds, then reclosed, and the divider ratio remeasured.

After eliminating the anomaly discussed in the following paragraph, approximately 140 switching operations were performed at 50 kV with no ratio offsets. Based on the earlier discussion of failure probability (see footnote 3), 140 failure-free operations indicate at least a 99.9999% confidence that the failure rate is ≤ 0.1 (1 in 10), 75.5% that it is ≤ 0.01. Therefore, it appeared that high-voltage switching did not cause ratio offset, at least up to half voltage, or 50 kV/module.

The following observations should be taken into account in any situation in which measurements with circuits such as this are made in conjunction with high-voltage switching. Five of the first 20 switching operations produced significant ratio offsets. Investigation traced these to the same residual dc voltage on C_{42} as had been found for grounding switch operations. However, the grounding switch had not been operated. Further investigation showed that removal of the 20 kV standard capacitor (C_J, fig. 7) eliminated the problem. The only reasonable mechanism seemed to be flashover of that capacitor, which would act in the same manner as operating the grounding switch. This would, in turn, require excessive voltage in the capacitor loop. Reduction of a long ground lead to a very short length eliminated the problem, with C_J remaining in the circuit. Evidently, switching surge voltages, even at 50 kV, induced ground loop voltages large enough to spark over a 20 kV capacitor.

4. ELIMINATION OF TRAPPED CHARGE

4.1 Divider Modification

Elimination of the trapped charge in the divider is accomplished as shown in figure 12. It consists of the addition of bleeder resistor R_{42} across C_{42}. A 10.5 MΩ value was chosen, using stock metal film resistors. This produces a 16-second time constant ($C_{42} + C_{AD} \cong 1.52$ μF) for bleeding the trapped charge away. Then the maximum possible ratio offset of 0.5% will be reduced to 0.01% in one minute, a negligible time in terms of the usual several hours on-line. R_{42} introduces a phase shift of $1/\omega R(C_{42} + C_{AD}) \cong 0.17$ mrad into the divider. This, in turn, is compensated for by 2-MΩ resistor R_{h3}, placed across C_{h3} in the high side of the auxiliary divider.

4.2 Tests of the Modified Divider

A total of 52 grounding switch operations, performed as described in section 3.1.1, produced a mean ratio drift of +12 ppm, with a standard deviation of 60 ppm. This gives at least a 65% probability that a significant offset will be seen no more than 2% of the time.

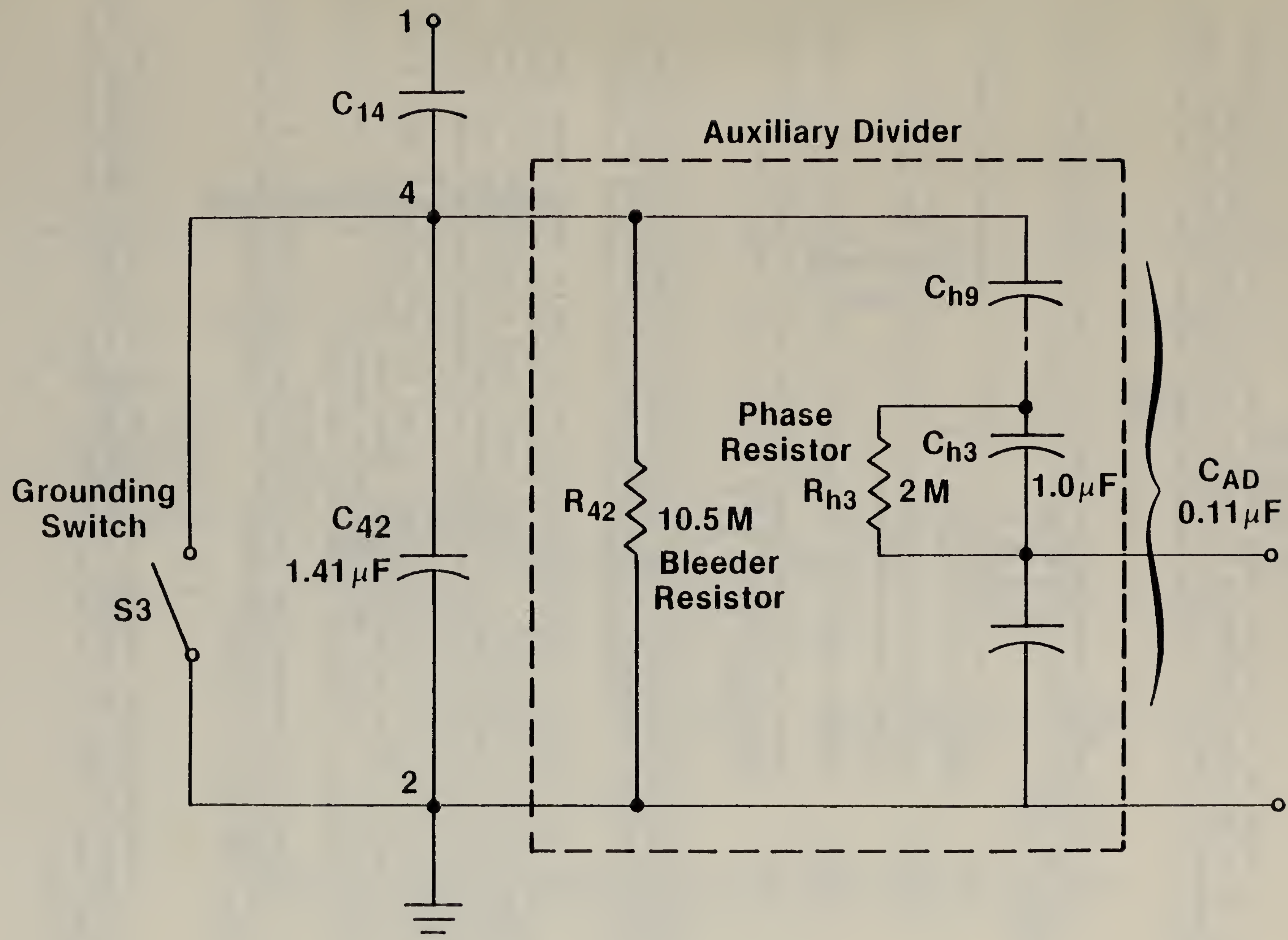


Figure 12. Divider modification to eliminate trapped dc voltage

5. SECOND WALTZ MILL TESTS

As noted earlier, high-voltage switching was carried out in the laboratory only up to 50 kV on a one-module divider, or to half the voltage stress encountered in the field. Since it did not seem prudent to extrapolate these results to full voltage, a second series of tests was carried out at Waltz Mill.

5.1 Test Procedure and Circuits

The measurement procedure was the same as for the first tests (sec. 2.2), except for the fourth step. The procedure consisted of the following principal steps:

Step 1. Calibration of the Waltz Mill 1500 kV compressed gas standard capacitor C_{SW} (fig. 2);

Step 2. Measurement of the standard divider ratio, using C_{SW} and the current comparator bridge (fig. 3);

Step 3. Repeat of step 2 for the Waltz Mill 1100 kV CCVT (fig. 4); and

Step 4'. Comparison of the standard divider and CCVT ratios using the current comparator bridge to cross check steps 2 and 3 (fig. 13).

Step 4' was changed from that for the first Waltz Mill tests (step 4) so that the current comparator bridge could be used throughout. This, plus an improved switching sequence, increased the speed and convenience with which the large number of switching operations (50) were performed and monitored.

The test procedure discussion in section 2.2 applies here, except that in step 4' (fig. 13), the ratio ρ_C/ρ_{SD} is measured directly, without the intervening 120:277 V transformer. In other words, step 1 determined the value of C_{SW}, the Waltz Mill standard capacitor (five measurements over the four-day test period yielded a mean value of 103.165 pF, which agreed with the value for the first Waltz Mill tests to within 0.01%). Steps 2 and 3 determined ρ_{SD} and ρ_C, respectively; step 4' compared ρ_{SD} and ρ_C; and the combination of steps 3 and 4' yielded an indirect value of ρ_{SD} for comparison with the direct value found in step 2. A closed set consisting of steps 2, 3, 4', and 2 was obtained initially and after each disconnect switch operation.

The detailed procedure was again as outlined in section 2.3. A total of 50 disconnect switch operations were performed, plus a 6-hour heat run at 300 kV on the final day of testing.

5.2 Test Results

In the measurement sequence outlined above, step 2, which is the direct measurement of ρ_{SD}, was presumed to be the basic, or primary, measurement, with steps 3 and 4' serving as a backup. However, analysis of the data showed the following:

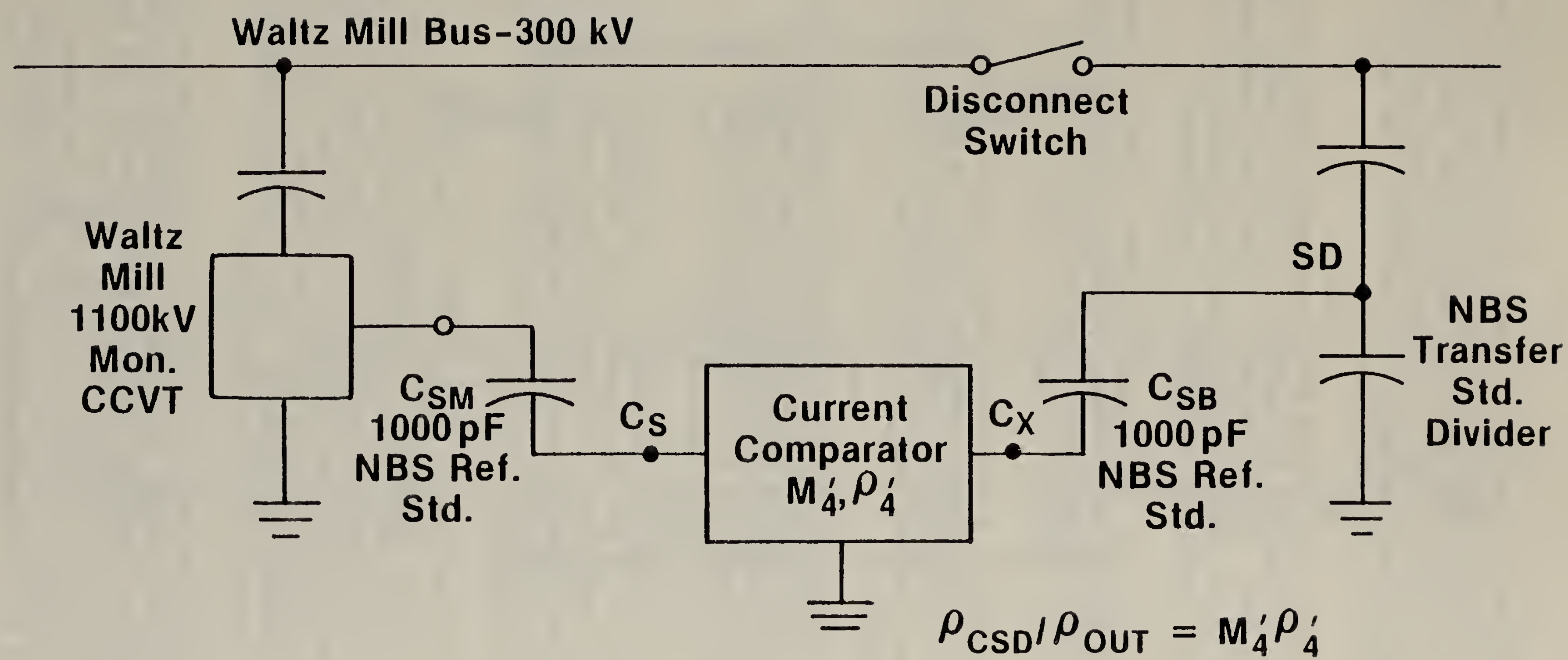


Figure 13. Step 4', comparison of the NBS standard divider ratio and the Waltz Mill monitoring CCVT ratio, using the current comparator

1. The repetition of step 2 at the end of the sequence revealed a highly consistent upward drift of ρ_{SD} from the initial measurement. The mean value of this drift was about 0.02%, with a standard deviation of about 0.01%. The first value was usually obtained approximately 30-45 seconds after switching; the second, essentially stable value, 3-6 minutes afterward.

2. The monitoring CCVT proved to be extremely stable, having a mean drift of less than 10 ppm against C_{SW}, with a standard deviation of only 70 ppm. Due to the drift in the direct measurement (step 2) discussed above, indirect measurement can therefore be given equal weight with the direct measurement. Furthermore,

3. The indirect value, no matter when taken, usually agreed closely with the <u>first</u> direct reading, instead of falling somewhere between the first and second direct values as expected (mean difference, 23 ppm, with a standard deviation of 0.01%, vs 218 ppm, 0.01%).

The above, apparently a peculiarity associated with the direct measurement, was discovered only after careful analysis of all the data. Examination of the data from the first Waltz Mill tests yields some evidence that this effect may have been present then, but was obscured by the much larger effect due to trapped charge.

At any rate, because of the close agreement between the direct-first-reading and the indirect data, the average of those two sets of values was used in assessing the effects of high-voltage switching on ρ_{SD}. As shown in figure 14, there appears to be little or no net effect (mean = -1 ppm, standard deviation = 80 ppm).

Figure 14, which shows the deviations in the measured divider ratios, may be explained as follows. The zero percent line represents, for each of the 50 disconnect switch operations, the next preceding shot as reference. Thus, taking two of the deviations as examples, the deviation of operation No. 10 from operation No. 9 is +0.016%; the corresponding deviation of operation No. 11 from operation No. 10 is -0.011%.

Further analysis has also revealed a fairly consistent downward shift in divider ratio of several hundredths of a percent, associated solely with going from truck power to Waltz Mill power. This operation involved disconnecting the truck from the Waltz Mill bus and moving it from about 8 m away to about 30 m away, plus changing the power source. It was also found that this shift occurs only at 300 kV for the direct measurement, but is already present at 100 kV for the indirect measurement. Past experience suggests that this is not an inherent characteristic of the system.

It should probably be concluded that the high-voltage switching effect is negligible relative to other measurement uncertainties once trapped charge is eliminated. However, pending further investigation of the apparent anomalies discussed above, it seems prudent to enlarge the estimated uncertainties assigned to the standard divider from the present 3σ value of 0.03% [1] to $3\sigma \cong 0.06\%$. This still leaves these uncertainties well within the value of 0.1% presently stated for CCVT calibrations.

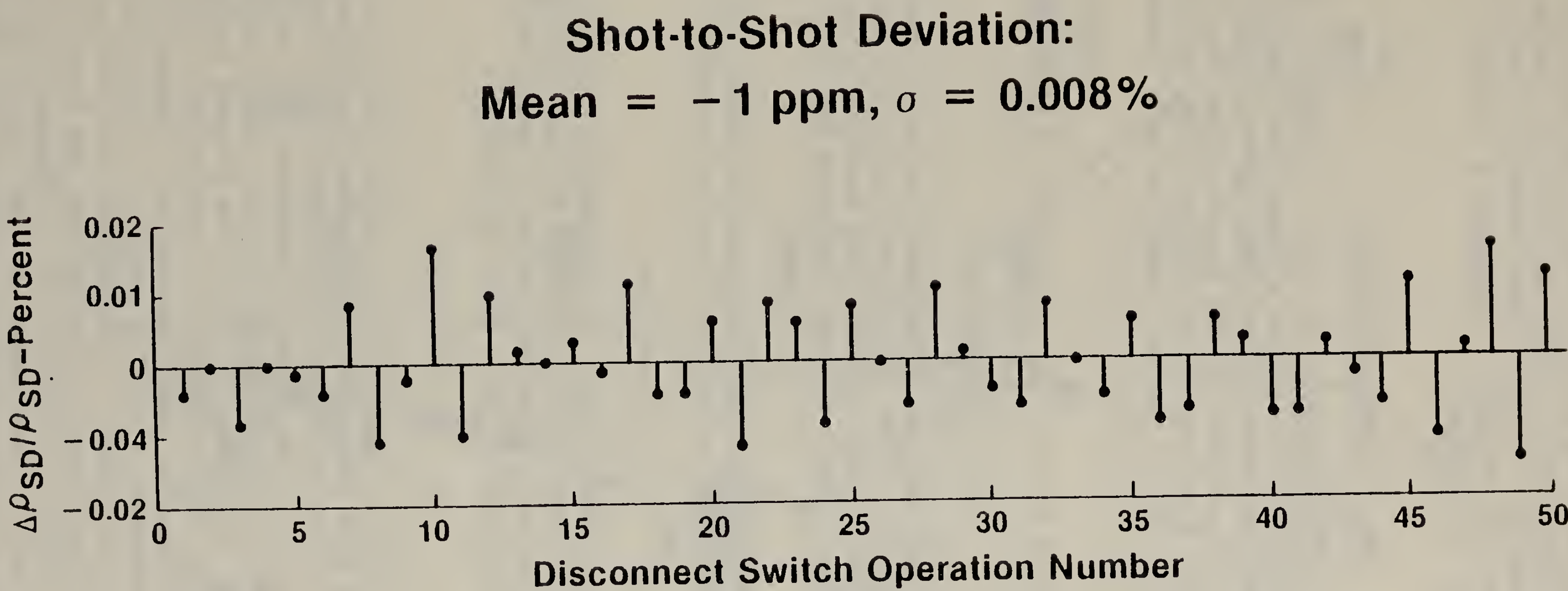


Figure 14. Shot-to-shot deviation of standard divider ratio, 50 disconnect switch operations, average of direct and indirect measurements

The heat run results were not entirely conclusive, possibly because they were done outside on a clear, chilly, windy day (8-11°C, average 12 mph wind). Earlier heat runs were made in the stable environments of indoor laboratories. However, the overall trend was the same, indicating a decrease in ρ_{SD} of the order of 0.03%, occurring in 2-3 hours.

6. SUMMARY OF RESULTS

High-voltage switching, per se, does not have a significant effect upon the accuracy of the CCVT calibration system's capacitive divider. Opening the grounding switch after connection to the line can trap charge on the low side, producing an error proportional to the square of the resulting residual dc voltage. This error has a maximum value of about 0.5%, and a probable value of nearly 0.2%, for a 500 kV divider. Addition of a bleeder resistor around the divider low side eliminates the error.

7. RELATION OF RESULTS TO THE GSU CCVT CALIBRATIONS

7.1 Introduction

As stated earlier, three sets of measurements at GSU triggered the investigation described in [1]. When that investigation did not explain some unexpected results obtained at GSU, one remaining possibility was some effect from high-voltage switching. This, in turn, generated the tests described in this report.

The grounding switch procedure was instituted in January 1980. Therefore, the first calibration, performed in May 1979, was not affected.

7.2 Assumptions

In the following discussion, it will be assumed that the only effect present is a positive ratio error in the standard divider, ranging from zero to 0.5% for a 500 kV divider with a probable value of approximately 0.2%. This error causes an equal negative ratio error in the CCVT.

7.3 The "V-Effect"

In the so-called "V-Effect," some results, particularly for C-phase (fig. 15, [1], reproduced here also as fig. 15) showed the second ratio value, or bottom of the "V," to be an average of about 0.3% lower than the other two values. This is the right order of magnitude and, according to figure 10, about 25% probable. It could explain the C-phase results if it is remembered that the offset was absent in 1979, then assumed that a 0.3% offset was present in March 1980, followed by a zero offset in December 1980. It appears from figure 11 that the above sequence has a probability of about 0.32 x 0.16, or 5%. Furthermore, a similar effect is present on one A-phase value (AW), but absent on the others. This not only involves two completely different switching operations than for C-phase, but the effect is not present in the other two A-phase values, as it would be if trapped dc voltage were the only perturbation. Finally, the trapped voltage effect, acting alone, dictates that all 1980 ratio values must be equal to or less than the 1979

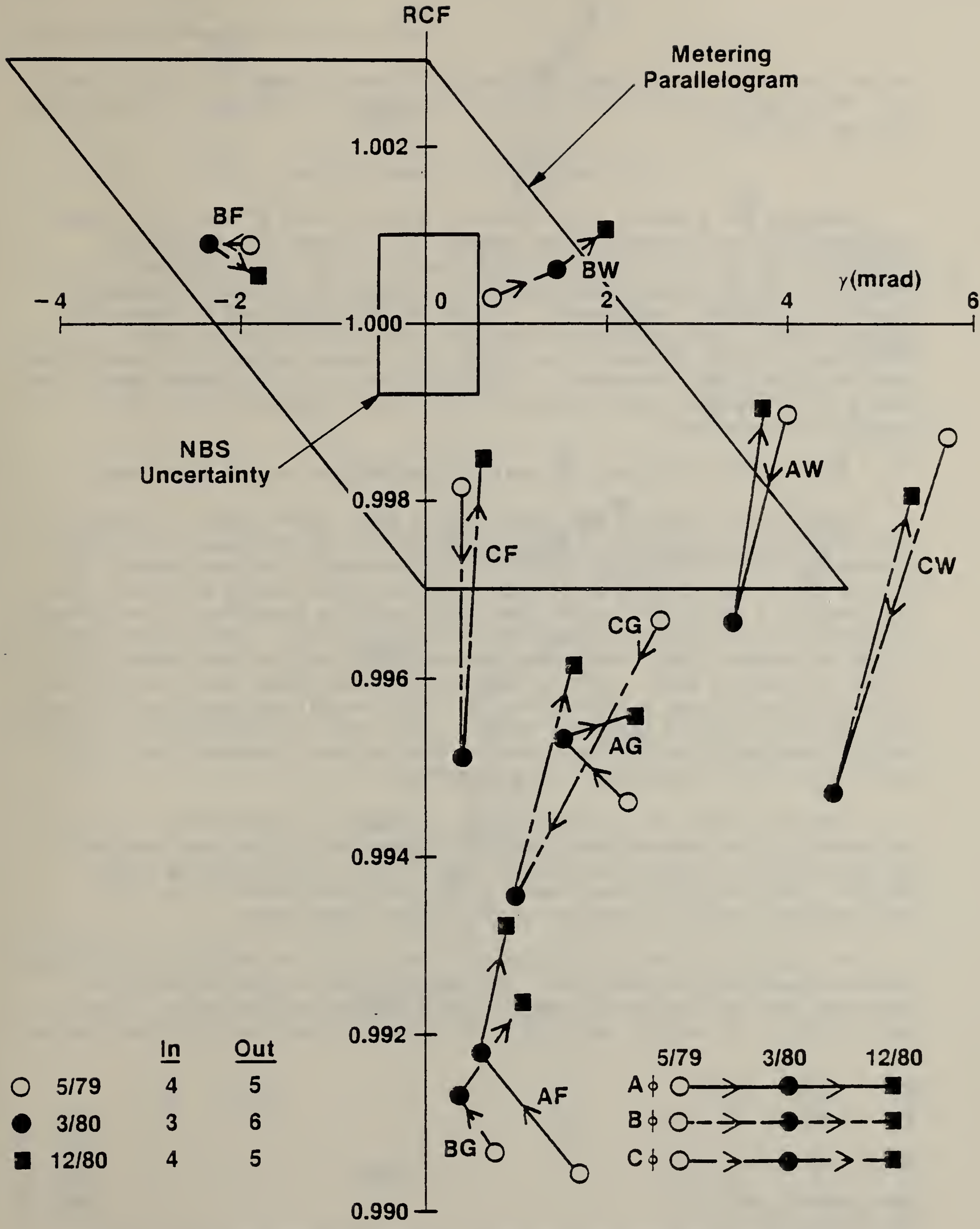


Figure 15. "Revised" history of X1X3 RCF and γ, May 1979 to December 1980, GSU calibrations

values (on the average, about 0.2% less). Figure 15 shows this not to be so. Thus, there is no obvious correlation between the trapped voltage effect and the "V-effect."

7.4 Applying the Probable Offset

Assuming the probable +0.2% standard divider ratio offset (i.e., -0.2% apparent CCVT ratio offset) to be present at all times, the effect was "corrected for" by shifting all 1980 values by +0.2%. This is shown in figure 16. Comparing the tabulated "In" and "Out" values[6] with those on figure 15, a slight "improvement" is seen for March 1980 and no change for December 1980. Even applying the maximum permissible offset of 0.5% (admittedly highly improbable for all of six consecutive switching operations) made no significant improvement. Other combinations of adjustment were tried, with similar results. Again, there is no obvious correlation with the trapped voltage effect.

7.5 Comparing Consecutive Switching Operations on the Same Phase

Since charge trapping has been shown to be a random event, it would be expected that two consecutive switching operations on the same phase should produce two sets of measured ratio values differing by the same amount for all the CCVTs connected to that phase. In the normal course of events, two such switching operations on the same phase would be separated by the period of months, or even years, between two calibration trips. One exception occurred at GSU in December 1980, when it became necessary to go on one phase twice, on two consecutive days. In this case, even though actual ratio offsets are unknown, it would seem probable (fig. 11) that the offsets would be different. This difference should then show up as a fixed shift in magnitude and direction for all comparable ratio values taken on the two days, assuming short-term stability of other variables in the measurement.

Since the first set of measurements was taken in the control house and the second at the make-up boxes (MUBs), a comparison of the data required the calculation of lead drop between control house and MUB due to burden current. This calculation was made, using utility-furnished burden and lead impedance data, and applied to the control house data.

The results are shown in figure 17. The vectors represent the differences between measurements on each tap. Not only are they widely different in magnitude, but two vectors are opposite in direction to the others. Once again there is no obvious correlation with ratio offset due to trapped charge.

---

[6]"In" is defined conservatively as being within the metering parallelogram plus the NBS uncertainty.

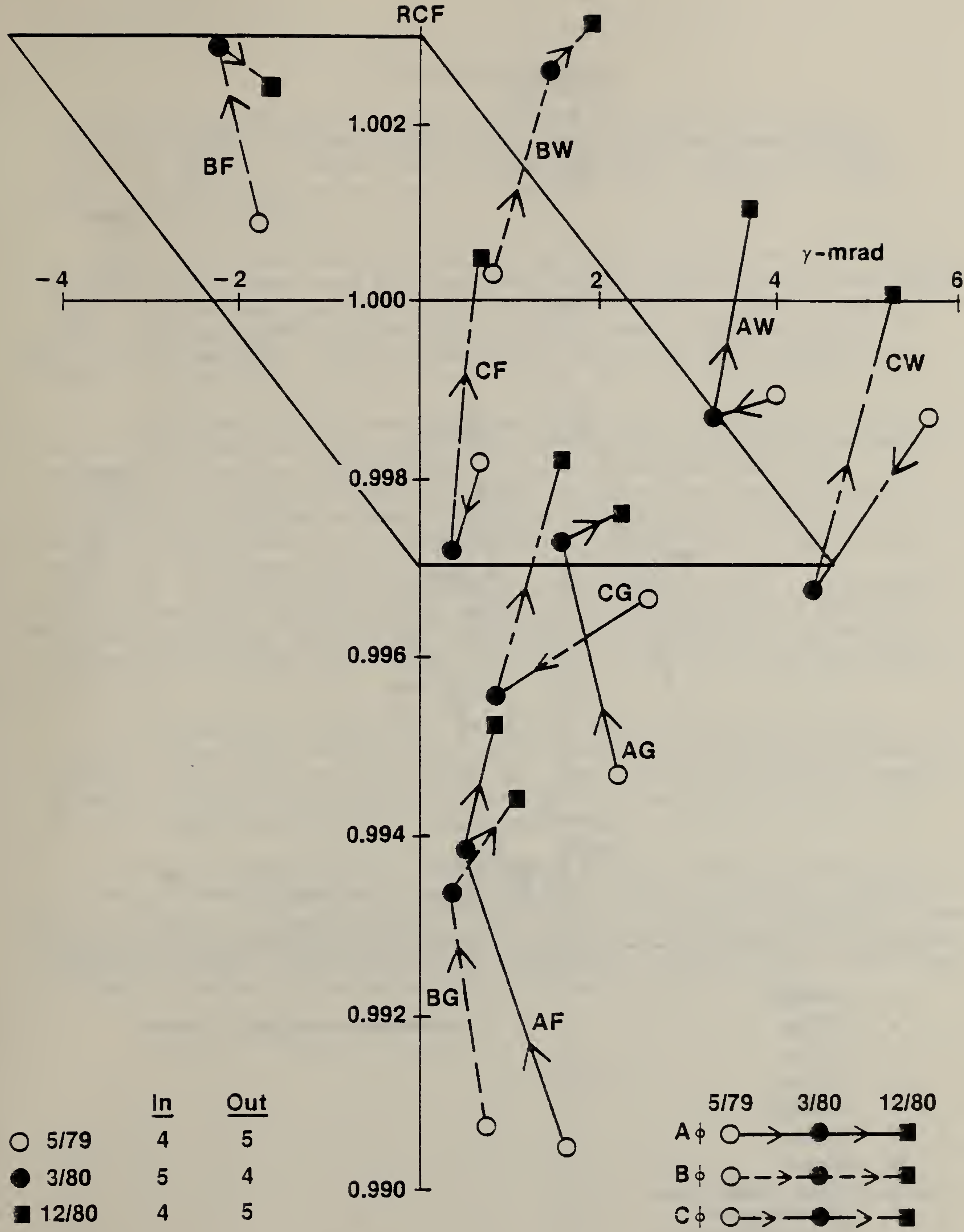


Figure 16. GSU "revised" March 1980 and December 1980 results adjusted upward by 0.2% (1979 results assumed correct)

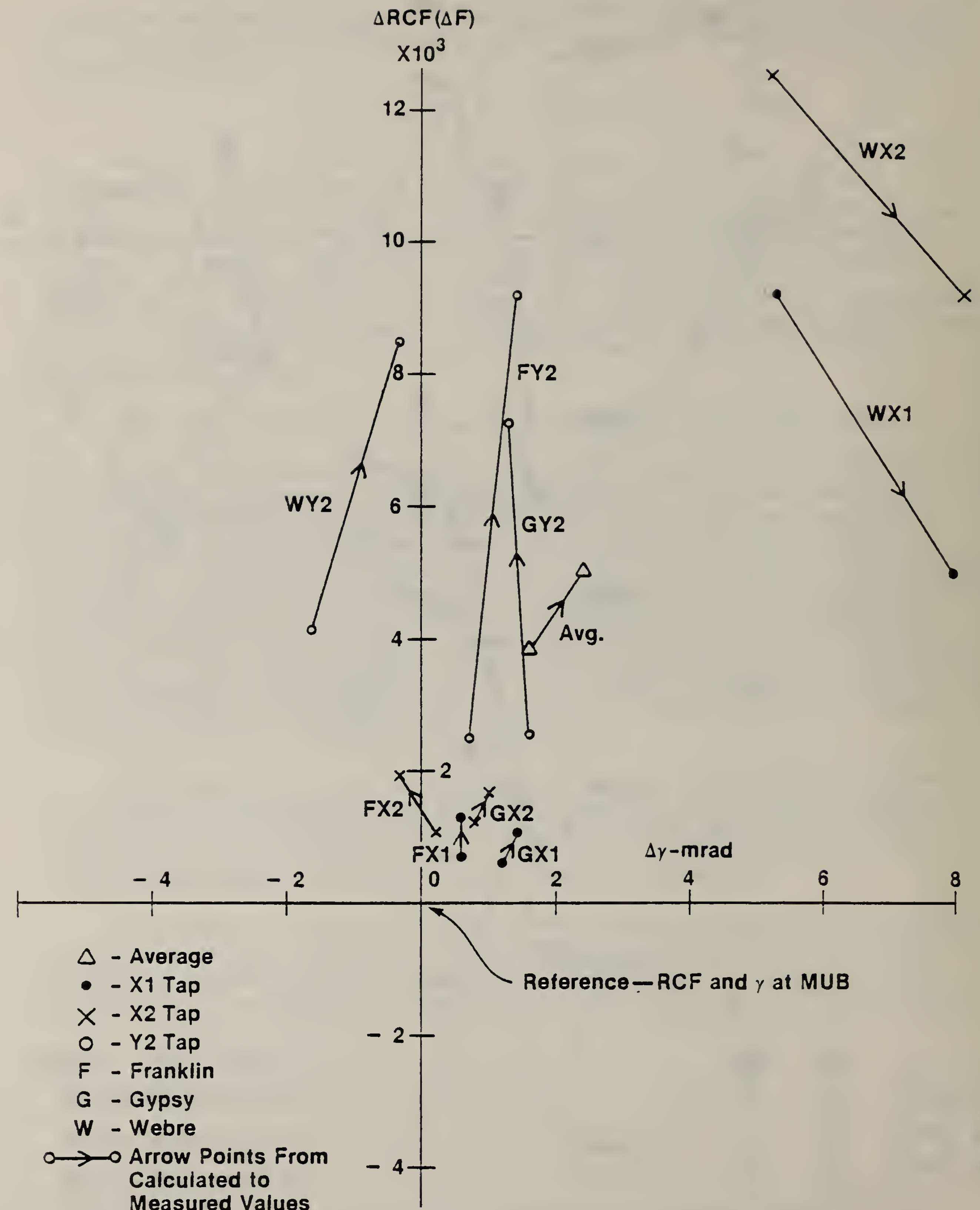


Figure 17. Calculated vs measured changes in RCF and γ, for one phase, from MUB to HSE, GSU, December 1980

8. DISCUSSION AND SUMMARY

High-voltage switching seems to have no significant effect on the capacitive standard divider's ratio, other than that from trapped charge on the low side in the absence of a bleeder resistor. Attempts to relate the dc voltage effect to the results of the GSU investigation [1] yielded no obvious correlation.

Data from calibrations performed at two other utilities while this effect was supposedly present were also analyzed. Not only was no obvious correlation found in either case, but as mentioned earlier (sec. 2.2), some extremely close agreement between NBS and factory results seemed contraindicative of any dc voltage effect. This was one of the reasons for not anticipating a high-voltage switching effect at the outset of the Waltz Mill tests.

In retrospect, it has been suggested that divider leakage resistances may be highly variable under field conditions, perhaps quite often low enough to quickly remove any trapped charge. This could be postulated as an explanation for the close agreements mentioned above, and for the absence of any obvious correlation between GSU or other calibration results and a possible ratio offset due to trapped charge. However, such variable leakage resistance would have to be $10^9\ \Omega$ or less ($\tau \cong 30$ min) to be at all effective. A leakage resistance of $10^9\ \Omega$ seems improbably low. Furthermore, it would manifest itself as easily detectable drift, amounting to several tenths of a percent, during those measurements for which several tenths of a percent initial offset was present. Such large drifts have never been seen in the field.

With or without a ratio error in the EPRI-NBS divider due to trapped charge, a significant proportion of the affected CCVTs were outside of metering tolerance. Many were well outside of it. Some marginal CCVTs might appear to be better if this error could be assumed and then removed by correcting the results. Others would actually appear to be worse.

Cumulative experience with CCVTs suggests that a long-term monitoring program for these devices would be useful. The Waltz Mill facility appears to be excellent for such a program. A dozen or so CCVTs from various sources (new, used, very old, taken-out-of-service, etc.) could be connected to a single bus. Computer and other facilities already in place for long-term cable tests should be readily adaptable to automated collection and analysis of data.

9. REFERENCES

[1] D. L. Hillhouse and D. A. Leep, Analysis of the calibration of metering CCVTs in a utility substation, Nat. Bur. Stand. (U.S.), NBSIR 82-2360 (Oct. 1981).

[2] C. J. Baldwin and J. W. Bankoski, Waltz Mill facility tests underground cables and also demonstrates feasibility of 1100 kV overhead systems, Westinghouse Engineer, Nov. 1973.

[3] D. L. Hillhouse, O. Petersons, and W. C. Sze, A prototype field calibration system for coupling capacitor voltage transformers (CCVTs), EPRI EL-690, Apr. 1978.

[4] D. L. Hillhouse, O. Petersons, and W. C. Sze, A prototype system for on-site calibration of coupling capacitor voltage transformers (CCVTs), IEEE Trans. Power Appar. Syst., Vol. PAS-98, No. 3, May/June 1979, p. 1026.

[5] D. L. Hillhouse, O. Petersons, and W. C. Sze, A simplified system for calibration of CCVTs in the substation, Nat. Bur. Stand. (U.S.), Technical Note 1155 (May 1982).

[6] N. L. Kusters and O. Petersons, The voltage coefficients of precision capacitors, IEEE Trans. Power Appar. Syst., Vol. PAS-82, No. 11, Nov. 1963, p. 612.

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 83-2666	2. Performing Organ. Report No.	3. Publication Date March 1983

4. TITLE AND SUBTITLE

EFFECTS OF HIGH-VOLTAGE SWITCHING ON THE EPRI-NBS COUPLING CAPACITOR VOLTAGE TRANSFORMER (CCVT) CALIBRATION SYSTEM STANDARD DIVIDER

5. AUTHOR(S)

David L. Hillhouse

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Sponsored in part by

Electric Power Research Institute
Palo Alto, California 94304

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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)*

This report presents the results of tests of the effects of high-voltage switching on the EPRI-NBS CCVT calibration system's capacitive standard divider, completing an investigation stemming from the results of three calibrations at a Gulf States Utilities substation.

Initial tests consisted of full-scale (300 kV) switching operations at EPRI's Waltz Mill test facility, during which the divider exhibited significant ratio offsets (average = +0.2%, maximum = nearly +0.5%). Tests were continued at the National Bureau of Standards (NBS), where it was determined that operation of a grounding switch, installed to protect the divider low side during high-voltage switching, caused ratio offset by trapping charge on the divider's low side capacitor. This resulted in residual dc voltage which changed the value of the divider's low-side capacitance. The addition of a bleeder resistor eliminated the problem in the laboratory. With the bleeder resistor in place, the Waltz Mill tests were repeated. Fifty high-voltage switching operations indicated a negligible shot-to-shot variation (average = -1ppm, σ = 80 ppm).

No obvious correlation was found between the ratio offsets described above and the results of CCVT calibrations performed while the effect may have been present in the divider. Experience indicates that a significant proportion of calibrated CCVTs is outside metering tolerance. Long-term simultaneous monitoring of a sizeable number of CCVTs is suggested.

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

calibration; capacitive divider; CCVT; error sources; high-voltage measurements; high-voltage switching; ratio offset; trapped charge; Waltz Mill tests.

13. AVAILABILITY

[X] Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
[X] Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

37

15. Price

$8.50