NBS TECHNICAL NOTE 1155

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

A Simplified System for Calibration of CCVTs in the Substation

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary

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Issued May 1982

National Bureau of Standards Technical Note 1155
Nat. Bur. Stand. (U.S.), Tech. Note 1155, 57 pages (May 1982)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1982

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A SIMPLIFIED SYSTEM FOR CALIBRATION OF CCVTs IN THE SUBSTATION

David L. Hillhouse, Oskars Petersons, and Wilbur C. Sze

Coupling capacitor voltage transformers (CCVTs) are widely used for the revenue metering of energy exchanged between utilities at EHV (345-500 kV) interties. These devices are installed permanently in substations, and must be calibrated there. Allowable error is ±0.3 percent and ±4.6 mrad (milliradians).

NBS developed, and has had in operation for several years, a prototype system for field calibration of these CCVTs. This prototype system is more accurate, more complicated, more bulky, and more costly than is essential for this application.

This report describes a simplified, lighter, and less costly CCVT calibration system, newly developed and field tested by NBS. The principal elements of this system are a portable reference standard transformer and moderate voltage power supply (14.4 kV), a modular capacitive transfer standard divider, and a voltage comparator. Results obtained with this system agree with the prototype to within ±0.03 percent and ±0.1 mrad.

The prototype system is installed permanently in a dedicated calibration truck. The new system could operate with a non-dedicated truck to transport the disassembled modular divider, and a van to transport the rest of the components and to serve as a field laboratory.

Key words: CCVTs; EHV revenue metering; energy metering; field calibration; 500 kV; 500 kV substation measurements; metering accuracy CCVTs.

1. INTRODUCTION

The coupling capacitor voltage transformer (CCVT) is a ratio device for reducing transmission line alternating voltages (230-765 kV rms, line-to-line) to 115 V rms to neutral for relaying, and/or metering [1].[1] As its name implies, the CCVT originated (in the 1920s) as a coupling capacitor used to couple telephone carrier current from high-voltage transmission lines. The basic circuits of its evolution into its present configuration are shown in figure 1.

In the early 1930's, a low-side capacitor was added and the resultant capacitive divider used for voltage monitoring and relaying (fig. 1(b)). Since the voltage of the secondary tap had to be several kilovolts in order to transfer significant energy, an intermediate iron-core transformer was added to reduce this voltage to standard secondary levels (fig. 1(c)). To improve the accuracy and greatly increase the energy transfer across the divider, a resonating inductor was next placed in the secondary of this transformer (fig. 1(d)) to tune out the high reactance of the capacitive divider.

In this form, the CCVT was accurate and stable enough for relaying and for routine voltage measurement, and it was so used for many years because of the cost advantage over conventional inductive voltage transformers (VTs). It was not, however, accurate enough for revenue metering (allowable errors of ±0.3 percent for ratio, ±4.6 mrad for phase angle) as specified in ANSI Std. C57.13-1978.

Beginning about 1950, transmission voltages moved upward through the EHV range (345-765 kV), and EHV circuits expanded to include many interties between systems. This created a need for metering at the EHV level. The increased cost and fragility of conventional VTs at these voltage levels produced the incentive for improving CCVTs to meet metering accuracy requirements. To accomplish this, the tuning reactor was moved to the primary of the intermediate transformer, stack capacitance and capacitive divider tap voltage were increased significantly, and the low-side capacitor was made an integral part of the stack capacitance instead of a separate unit. The basic schematic circuit of the resultant present-day metering CCVT is shown in figure 1(e). It consists of a modular capacitive divider which reduces line voltage V_1 to voltage V_2 (10-20 kV), a series resonant inductor to tune out the high impedance of the divider, and an intermediate voltage transformer to reduce V_2 to voltage V_b (115 V).

As stated above, the principal impetus for applying the CCVT to metering was the higher cost, bulk, and fragility of the conventional VT

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

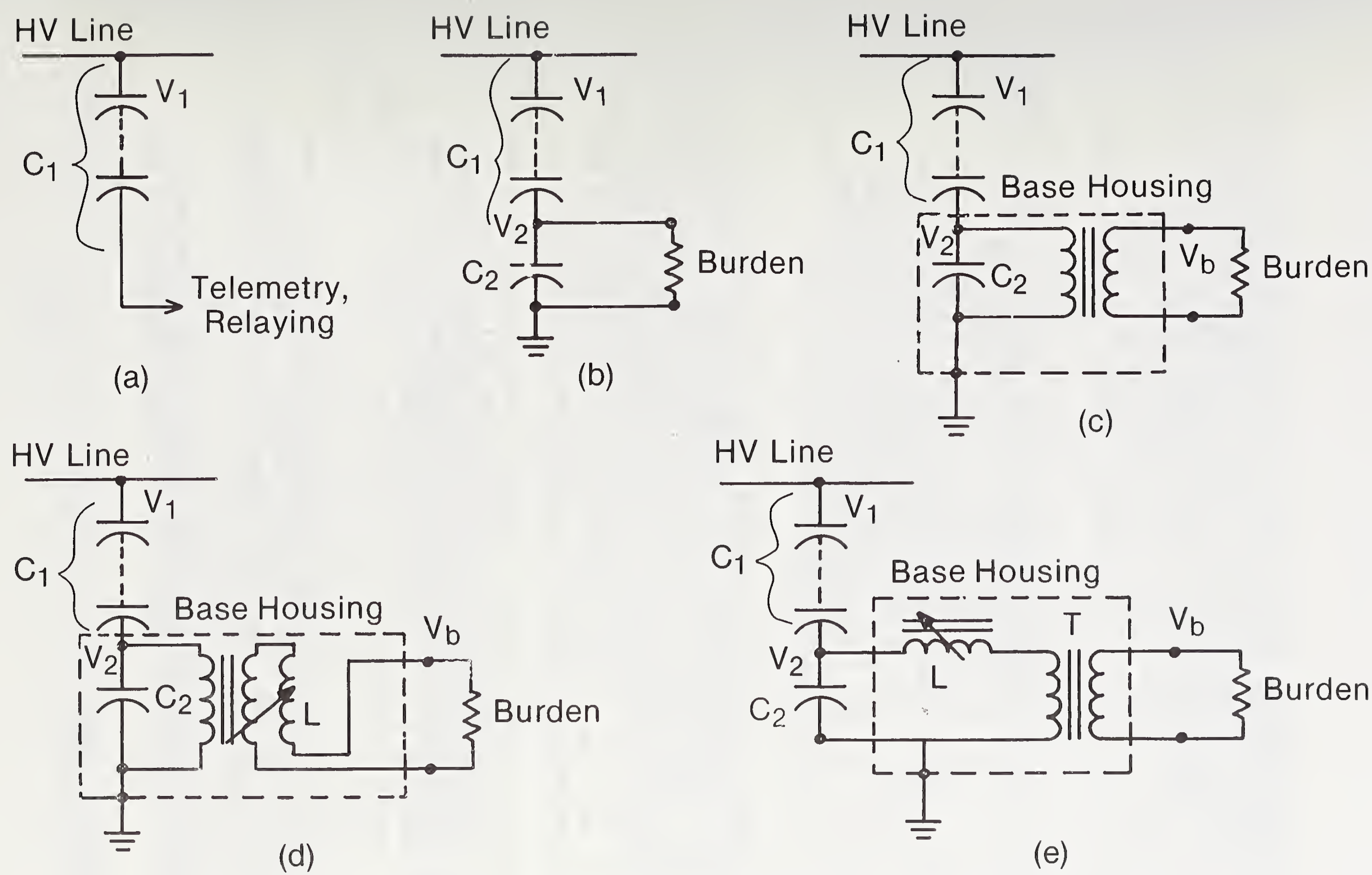


Figure 1. Evolution of the metering accuracy CCVT:
(a) Carrier current coupling capacitor,
(b) Simple capacitive divider,
(c) Intermediate transformer added,
(d) Tuning reactor added to secondary,
(e) Modern metering accuracy CCVT.

at voltages above 345 kV. Revenue metering was for many years the exclusive province of the VT, for which its simplicity, stability, and long life make it ideally suited. The VT depends primarily on its turns ratio to yield the actual voltage ratio. This ratio is modified only slightly by leakage and magnetizing impedances and stray capacitances, and has very little temperature, voltage, or aging dependence. In fact, a well-designed VT can be installed and essentially "forgotten" for its 30-50-year lifetime, unless its burden is changed.

The CCVT is a more complicated device whose basic accuracy and stability depend strongly on the properties of its paper and oil capacitor stack, and, to a lesser extent, on the inductance of its series tuning reactor. The capacitor has considerable sensitivity to temperature, voltage, aging, and proximate objects, although these effects are mitigated considerably in the capacitance ratio by the identical construction of both arms of the divider. In practice, the mismatches in capacitor characteristics and ambient conditions for the two arms are small, but not insignificant if ratio uncertainies less than ±0.3 percent are required.

Aside from the properties discussed above, the CCVT has one other potentially serious weakness - it can fail without the failure being detected immediately. Its capacitor stack consists of a large number of individual capacitors ("rolls") in series, one or more of which can short out, introducing a serious ratio error (typically >0.3 percent per "roll" in a 500-kV CCVT) without detectably affecting the stack's operation. On the other hand, if a turn shorts in a VT, failure will be detected because it is immediate and catastrophic.

Theoretical properties aside, the CCVT is less thoroughly proven than the VT, for which there is a record of over half a century of development and application. Enough in-service and other data have been accumulated on the CCVT to leave the prospective user with some reasonable doubts as to its reliability and stability [2,3].[2] Since the device is installed permanently in the substation, it must be calibrated there.

A prototype system for field calibration of CCVTs was developed and has been in service at NBS for several years. This system is described in [4] and [5]. Two other systems which have seen limited application are described in [2] and [3].

Although the prototype system has operated quite successfully, it is basically a research system. Experience has shown that it has

[2]See also [4], pp. 2-5.

a number of features probably not essential for routine calibration service, and that a simplified system is feasible - particularly since the accuracy of the prototype system is better than is required in the field. This report describes such a simplified calibration system, which has since been developed at NBS.

2. THE PROTOTYPE NBS SYSTEM

In order to better delineate the similarities and the differences between the new system and the prototype, and to illustrate the simplifications achieved, the prototype system will now be reviewed. This system consists of five principal elements:

(1) A high-voltage compressed gas standard capacitor,
(2) A current comparator bridge,
(3) A 100-kV resonant power supply,
(4) Its control console, and
(5) A high-voltage modular capacitive divider, which serves as a transfer standard.

Items (1), (2), (3), and (4) above are installed in a calibration truck which serves as a completely self-contained field calibration laboratory. Item (5), the modular divider, is broken down into its component modules and transported to the field in the same truck. This arrangement is shown in figure 2. When the system arrives at the substation, the off-load hatch is opened, the divider modules are removed, and the divider is assembled for use.

CCVT calibration with the prototype system consists of four steps:

Measurement 1: Measurement of a series of one-module dividers, made up of each standard divider module in turn, at above rated voltage (125-150 percent), using the resonant power supply.

Measurement 2: Calibration of the compressed gas high-voltage capacitor (C_{ST}) against a reference standard capacitor (C_{SB}), using the current comparator bridge.

Measurement 3: Calibration of the ratio of the standard divider against the ratio of compressed gas capacitor C_{ST} and reference capacitor C_{SM} at 100 kV, using the current comparator bridge and the high-voltage resonant power supply.

Measurement 4: Calibration of the CCVT by direct comparison with the standard divider, using the current comparator bridge.

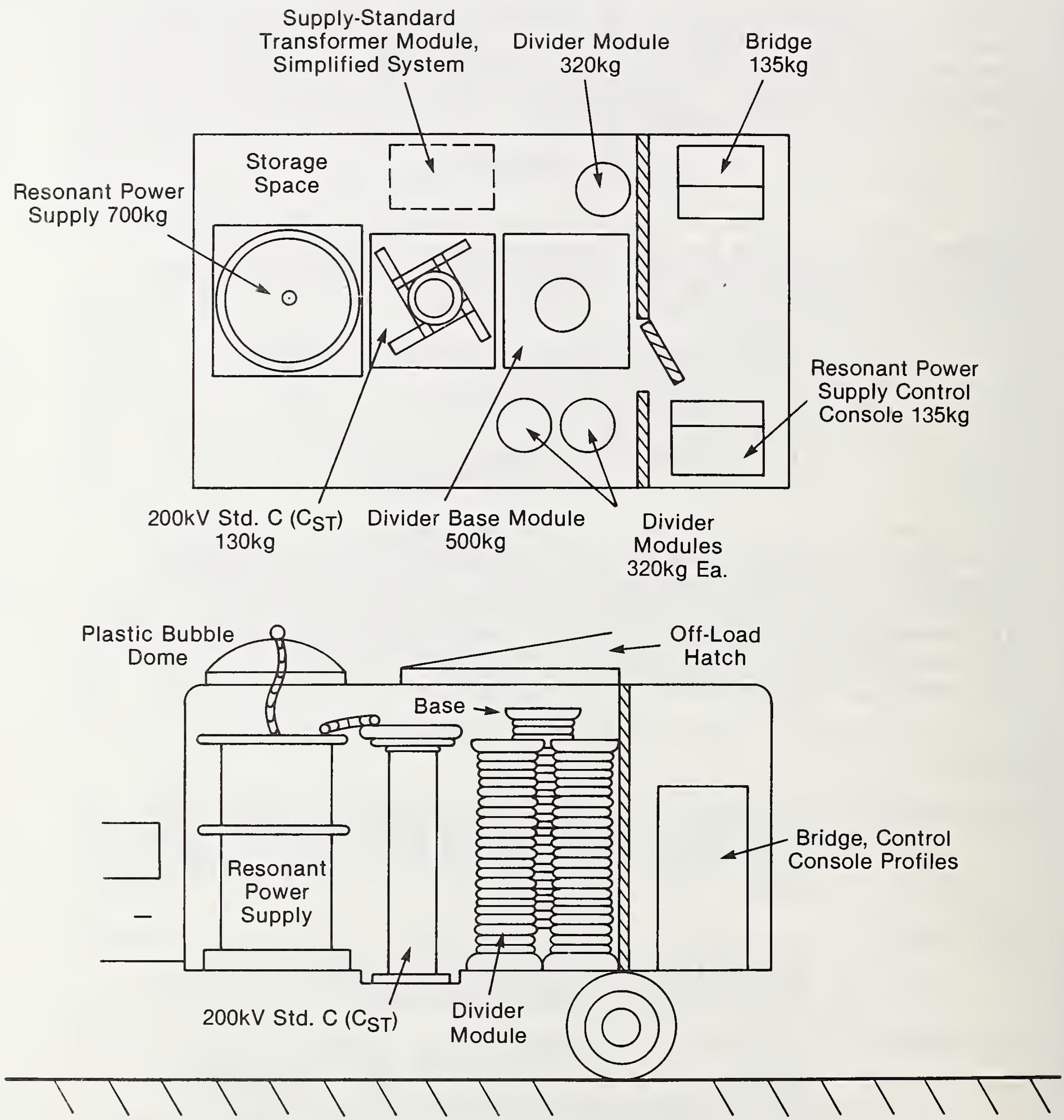


Figure 2. Approximate layout for transporting CCVT calibration system to the field in truck.

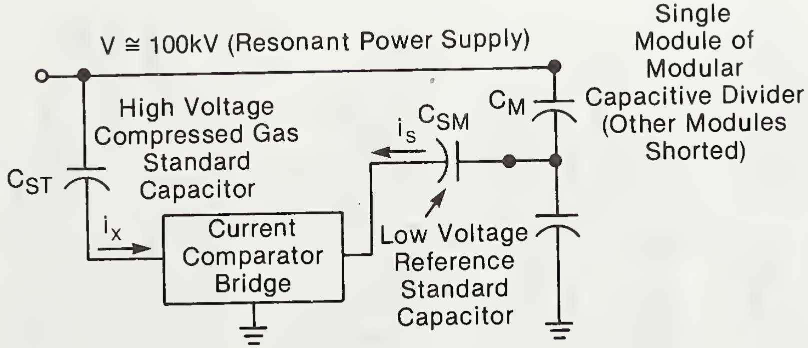
These steps are shown schematically in figure 3. The first measurement is not actually part of the CCVT calibration. It is a preliminary step (proof test or "hipot") in which each capacitor module in the transfer standard divider is subjected to up to 150 percent of its rated voltage for five minutes, and the ratio of the resultant one-module divider measured with C_{ST} and C_{SM} as references. This gives assurance that the module is intact and safe for connection to the utility bus. High voltage is furnished to C_{ST} and module C_M by the resonant power supply. Modules not being measured are bypassed with shorting straps. This measurement will detect the shorting of one or more "rolls" in a given module. Note that the circuit configuration is the same as for measurement 3.

The calibration of the CCVT is encompassed by measurements 2 through 4. Measurement 2 establishes the ratio $\rho_2 = (C_{SB}/C_{ST})$ of low-voltage reference capacitor C_{SB}, mounted in the bridge, and high voltage compressed gas capacitor C_{ST}, using an auxiliary 250-V power supply. (The ratio of interest is C_{SM}/C_{ST}. C_{SM} equals C_{SB} to a few parts per million. Equipment configuration makes it more convenient to measure C_{SB}/C_{ST}.) This measurement is required because C_{ST} has a temperature dependence of about 25 ppm/°C, and may drift during a day's measurements. The low-voltage calibration values can be used at high voltage because the voltage dependence of the compressed gas capacitor is negligibly small [6]. Measurement 3 uses standard current comparator bridge techniques [7,8], and the ratio ρ_2 obtained in measurement 2 to determine the ratio ρ_S of the transfer standard divider at approximately 100 kV.

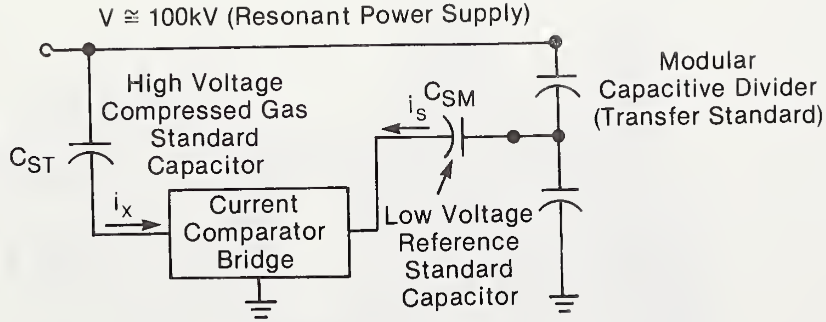
Measurement 4 is the final step, in which the on-line CCVT is calibrated against the transfer standard divider, using the divider ratio established in measurement 3. This is normally a 1:1 comparison ($\rho_4 \cong 1.0$), since the divider ratios are nominally equal to the industry standard values, e.g., 1800, 2500, and 3750 to 1, for 230, 500 and 765 kV, respectively. The divider is connected to the test piece bus for this measurement.

Since the ratio of the standard divider and the capacitance of the compressed gas capacitor may drift slightly during a calibration, measurements 2 and 3 are repeated afterward and the new values used to interpolate any required corrections. Phase angle drift is insignificant.

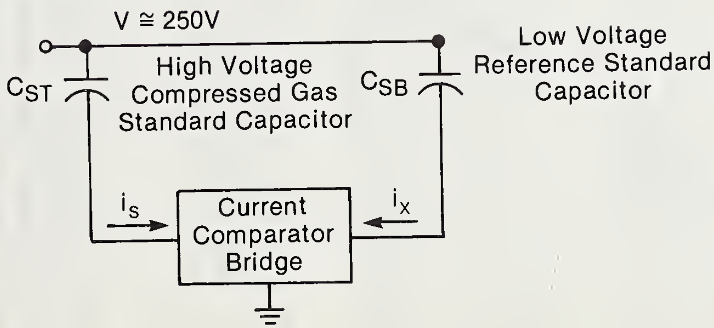
The system is arranged so that test results may be combined to obtain the ratio correction factor (F_t) and phase angle (γ_t) of the test piece, per conventional definitions for VTs (ANSI/IEEE C57.13-1978). F_t is obtained (after small corrections for divider voltage and temperature dependence, proximity effects, etc.) from the product of the bridge ratio readings from measurements 2, 3, and 4. γ_t (mrad) is the sum of the three corresponding bridge dissipation factor (DF) readings:



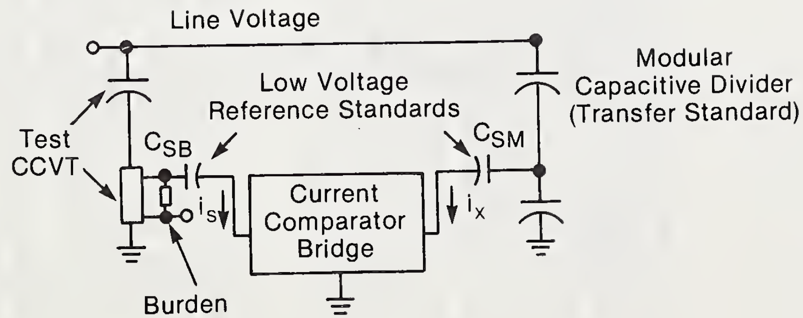
Meas. 1. Capacitance, Individual Standard Divider Modules, at 125% Rated Voltage



Meas. 3. Calibration of Transfer Standard at Reduced Voltage



Meas. 2. Calibration of High Voltage Compressed Gas Standard Capacitor at Low Voltage



Meas. 4. Calibration of CCVT at Line Voltage

Figure 3. Four-step calibration procedure for CCVTs, using the prototype system.

$$F_t = \frac{\rho_2\rho_3\rho_4}{\rho_{tN}} \qquad (1)$$

$$\gamma_t = (DF_2 + DF_3 + DF_4) \qquad (2)$$

where

ρ_{tN} = nominal CCVT ratio, e.g., 1800, 2500, 3750,

F_t = value by which ρ_{tN} must be multiplied to obtain the true CCVT ratio,

γ_t = angle by which the secondary voltage leads the primary voltage, mrad,

ρ_2 = bridge ratio reading, measurement 2, etc., and

DF_2 = bridge DF dial reading, mrad, measurement 2, etc.

Sources of uncertainty in the prototype system, in order of importance, are the high-voltage capacitive transfer standard divider, the high-voltage compressed gas standard capacitor, the current comparator bridge, and the low-voltage reference capacitors. Most of this uncertainty is believed to reside in the divider, stemming from voltage dependence, temperature dependence, including self-heating, and proximity effects. Detailed analysis was carried out in [4], as a result of which it was concluded that a reasonable estimate of uncertainties for the system would be ±0.05 percent for ratio and ±0.3 mrad for phase angle. This analysis was based on a 500-kV system. Errors are expected to be larger for a higher voltage system.

3. DESCRIPTION OF THE SIMPLIFIED SYSTEM

As discussed in the preceding section, the prototype system has five principal components: (1) a modular capacitive transfer standard divider, (2) a high-voltage compressed gas standard capacitor, (3) a current comparator bridge, (4) a 100-kV resonant power supply, and (5) its control console. The transfer standard divider is an essential element and cannot be replaced, since it is the link to the EHV bus. The 200-kV capacitor and the 100-kV resonant power supply can be replaced if a lower divider calibration voltage (e.g., 10-20 kV) can be tolerated. This, in turn, requires that the transfer standard divider have acceptable voltage dependence from the lower calibration voltage to rated voltage, and that there be an acceptable moderate voltage standard to replace the compressed gas capacitor. Elimination of the expensive current comparator bridge requires an adequate but simpler comparator. These requirements have been met in the simplified system to be described now.

As developed, the simplified system has three principal components: (1) the modular transfer standard divider, (2) a combined moderate voltage (14.4 kV) supply transformer and reference standard transformer, and (3) a voltage comparator. These are connected as shown in figure 4, as used in a two-step calibration procedure.

3.1 Calibration Procedure

The nomenclature "C3" and "C4" used for the measurement numbers below relates these calibration steps to the corresponding steps in the prototype system. The "C" stands for voltage "comparator." The subscripts "C3" and "C4" in the terms refer also to measurements C3 and C4.

In measurement C3 (fig. 4(a)), the standard transformer T2 and the transfer standard divider are connected in parallel to the supply transformer T1. The voltage comparator compares the two output voltages V_T and V_S. From the comparator outputs (ratio $\alpha_{C3} = |V_S/V_T|$ and phase angle $\gamma_{C3} \equiv \gamma_S - \gamma_T$), the ratio and phase angle of the standard divider are found as

$$\rho_S = \rho_T/\alpha_{C3} \tag{3}$$

$$\gamma_S = \gamma_T + \gamma_{C3} \tag{4}$$

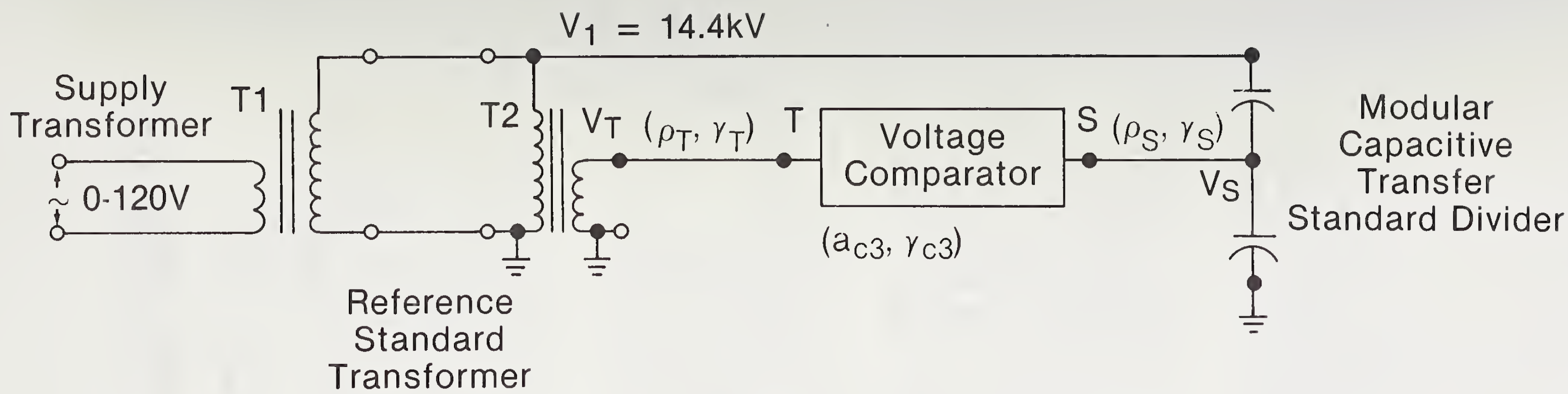
The ratio ρ_t of the standard transformer is determined in a laboratory calibration, using techniques outlined in [7] and [8].

In measurement C4 (fig. 4(b)), the calibrated transfer standard divider is connected to the EHV line in parallel with the CCVT to be tested, and the output voltages V_t and V'_S compared. From the comparator outputs, where $\alpha_{C4} = |V'_S/V_T|$, and $\gamma_{C4} \equiv \gamma_S - \gamma_t$, the ratio correction factor F_t and phase angle γ_t of the test CCVT are found as

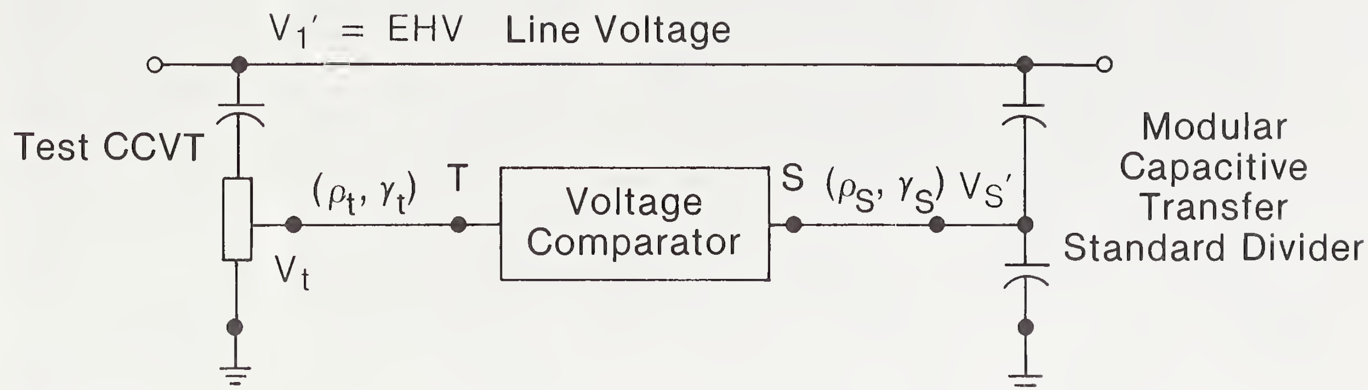
$$F_t = \left(\frac{\rho_T}{\rho_{tN}}\right)\left(\frac{\alpha_{C4}}{\alpha_{C3}}\right) \tag{5}$$

$$\gamma_t = \gamma_T + \gamma_{C3} - \gamma_{C4} \tag{6}$$

where ρ_{tN} is the nominal ratio of the test piece, e.g., 2500:1 for a 500-kV metering tap. Details regarding the derivation of the above equations will be found in appendix A-2.2.



(a) Measurement C3.



(b) Measurement C4.

Figure 4. Schematic diagram, simplified calibration system:
(a) Measurement C3 - calibration of transfer standard divider,
(b) Measurement C4 - calibration of CCVT.

3.2 System Components

3.2.1 Standard Divider

The modular divider is common to both the prototype and the simplified systems. A detailed description of the original divider is given in [4]. Much of that information is still valid, but the auxiliary divider and some other details have been modified. Those changes are documented below.

An elementary circuit diagram of the divider is shown in figure 5. The high side (C_{14}) consists of a stack of 138-kV (80 kV to neutral) CCVT capacitor modules, each having a capacitance of approximately 0.016 μF. The number of modules used depends on the line-to-line voltage (two for 230 kV, three for 500 kV, etc.). The base module has a special nominal 1-kV tap brought out on terminal 4 (C_{42}). This tap is not present on standard base modules, which are tapped at either 10 or 20 kV, depending on the manufacturer.[3] The auxiliary divider (C_{hi} and C_{Lo}) reduces the terminal 4 voltage to the nominal metering and relaying voltages found on CCVTs, i.e., approximately 115 and 66 V, respectively.

The divider has three switch-selectable ratios (S1, fig. 5), nominally equal to 2500:1, 4500:1, and 2250:1 for a three-module, 500-kV configuration. The first two are standard ANSI/IEEE C57.13-1978 ratios. The third is for future use at 765 kV, and would give nominally the ANSI standard 3750:1 with a five-module divider. Other ratios can be added if desired. The exact nominal ANSI ratios are provided only for convenience in calculations and in spotting gross errors,[4] since the actual divider ratio is determined (measurement C4) during each calibration.

Switch S3 protects the auxiliary divider from switching surges by shorting it while the divider is being connected to or disconnected from the bus. S2 is open during switching to prevent surges from travelling down the signal cable toward the instrumentation. Disposition of leads, including the deliberate addition of a small amount of inductance, provides further protection. The auxiliary divider is constructed of stable computer-grade capacitors. Detailed circuit diagrams and further discussion are contained in appendix A-5.

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[3]Note that such base modules must be specially ordered.

[4]Exception - since the voltage comparator has a maximum range of 1.1:1, this puts some restrictions on the nominal ratio. For more detail, see sections 3.2.2 and 3.3.1.

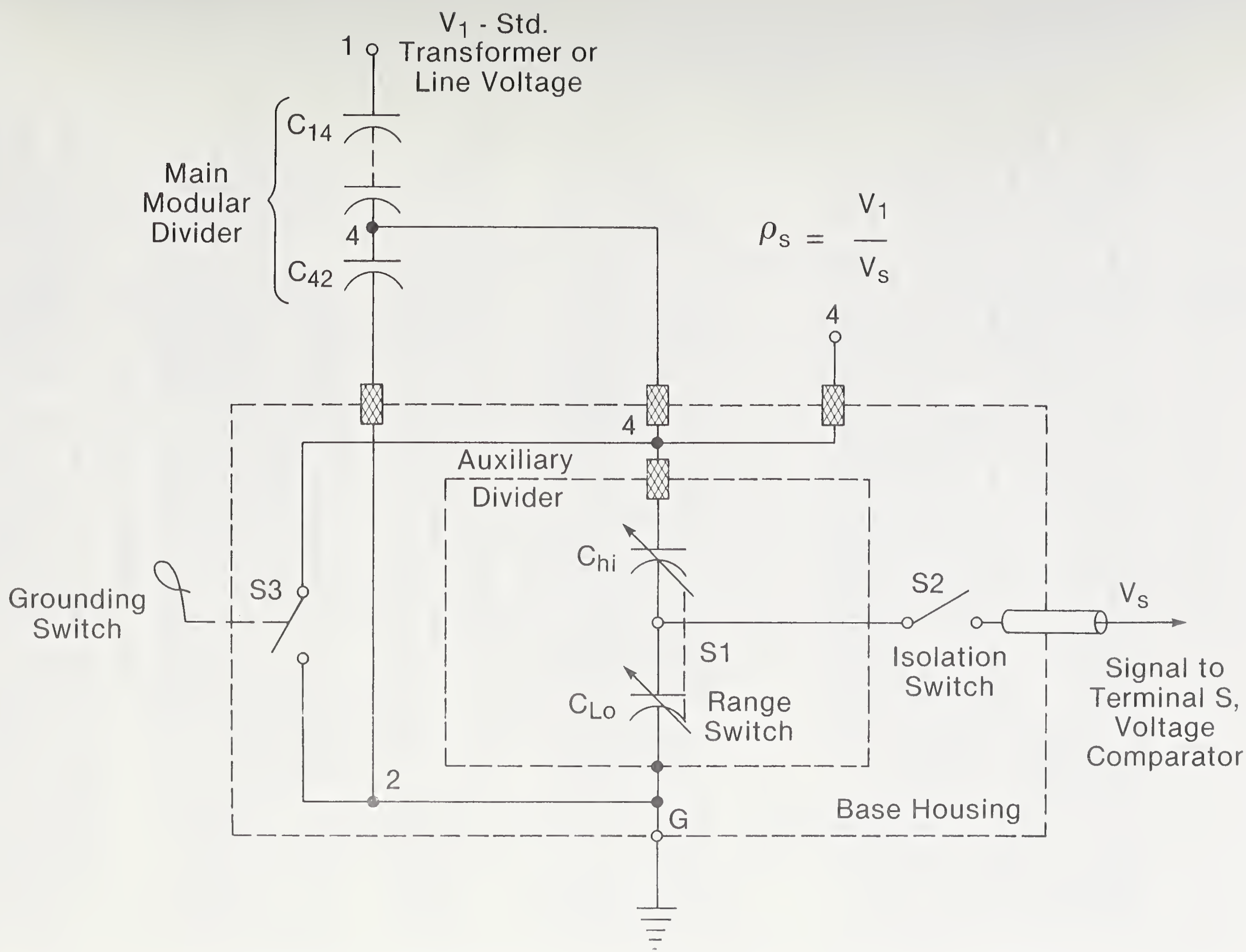

Figure 5. Basic circuit of the modular capacitive standard divider.

3.2.2 Voltage Comparator

The basic circuit diagram of the voltage comparator is shown in figure 6. This is the circuit encompassed by the voltage comparator block in figure 4. The comparator has three principal elements: the inductive voltage divider (IVD) T4, the quadrature circuit, and the detector circuit. T4 is a six-dial precision variable autotransformer with a ratio range of 0 to 1.11 .... In measurement C3, T4 compares a portion ($V_A = \alpha_{c3} V_T$) of standard transformer voltage V_T with the in-phase portion of standard divider voltage V_s, for determining ρ_s in eq (3). The quadrature circuit takes $\alpha_{c3} V_T$, accurately subdivides it, phase shifts the fraction by 90°, and reinjects it in series with the in-phase portion via transformer T3. The range of the quadrature circuit is ±(0-100) mrad. Balance between V_T and V_s is obtained by adjusting T4 and quadrature voltage $j\gamma_c V_A$, and is

$$V_s = \alpha_{c3} V_T (1 + j\gamma_{c3}) \tag{7}$$

where $j\gamma_{c3}$ is the proportion of $\alpha_{c3} V_T$ reinjected at 90° by T3. In measurement C4, T4 compares a portion ($V'_A = \alpha_{c4} V_t$) of CCVT voltage V_t with the in-phase portion of standard divider voltage V'_s. Balance is obtained when $V'_s = \alpha_{c4} V_t (1 + j\gamma_{c4})$. The detector circuit consists of a commercial tuned detector preceded by a twin-T filter to eliminate harmonics (found necessary in order to operate with this detector in the substation - see section 4.5.2 and appendix A-4 for further discussion).

Note that since the IVD (T4) has an output-to-input ratio range of 0 to 1.11 ..., i.e., α_c = 0 to 1.11 ..., V_s, figure 6, can be no more than 1.11 ... times V_T, and standard divider ratios must be selected so that a tap is available at no less than 1/1.11 ... times the ANSI ratio of the CCVT.

In addition to the functions described, transformers T3 and T5 also provide needed isolation between circuit components. T6 and T7, shown pictorially, are coaxial chokes [9,10]. These are special 1:1 transformers placed in the incoming signal lines to eliminate ground loop voltages, a serious source of error invariably encountered in the substation. These devices and their function are described in more detail in appendix A-6. The comparator is mounted in a single standard 19-inch (483-mm) cabinet, as shown in figure 7.

3.2.3 Standard Transformer

The standard transformer T1 is a commercial unit with a maximum rating of 14.4 kV, having ratios from 1:1 to 120:1 (14400:120 V). It is commonly used as a laboratory standard, adjusted at the factory to within approximately ±0.01 percent and ±0.02 mrad of nominal, as confirmed by calibration in our laboratory. Its ratio is highly stable and insensitive to its environment (<0.01 percent change from 5-30 °C) as confirmed by calibration in the substation using the prototype system.

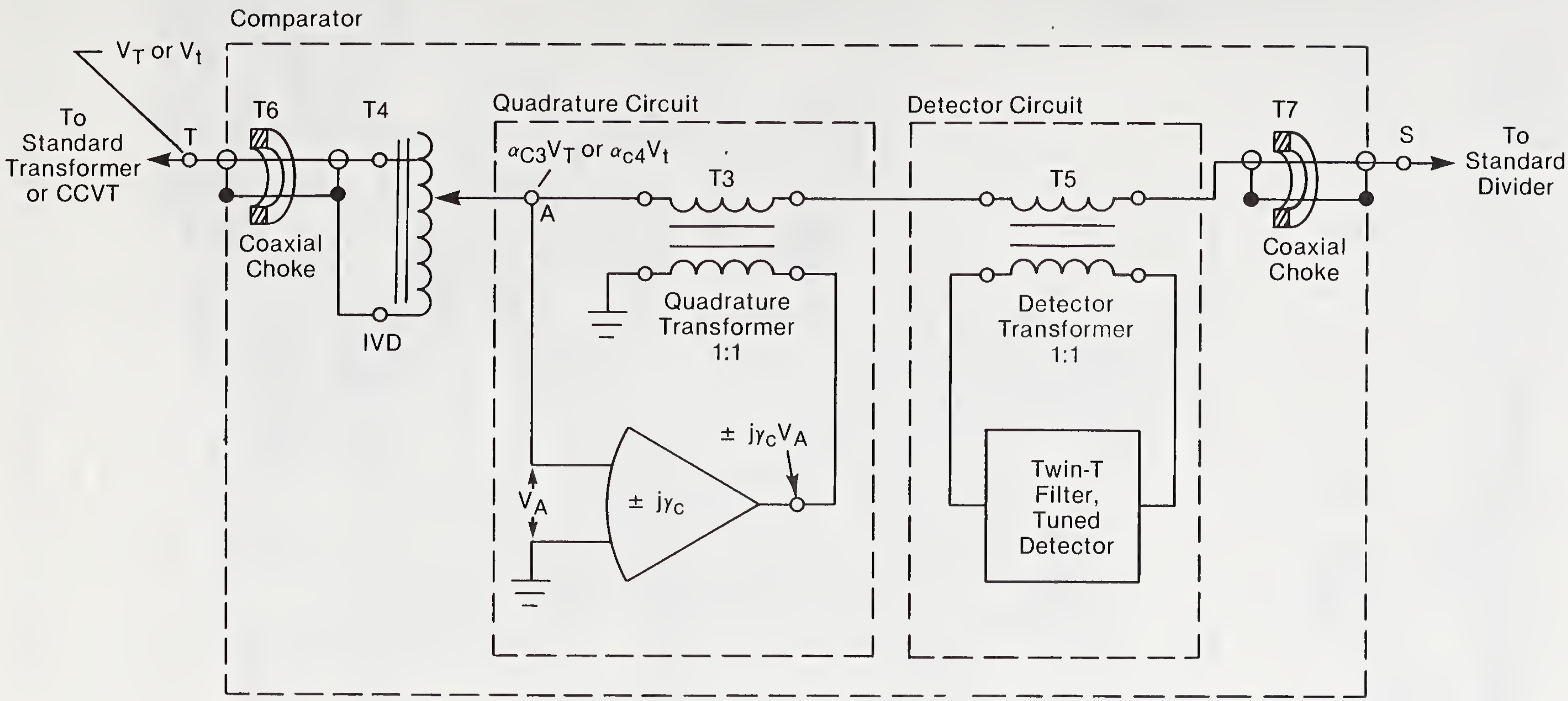

Figure 6. Basic circuit of the voltage comparator.

Figure 7. Voltage comparator assembly.

3.2.4 Supply Transformer

The supply transformer is a companion unit of the same construction and voltage rating as the standard transformer. The two are packaged as a single two-module unit. In principle, any power transformer rated at about 15 kV and 1 kVA could be used to power the system. The assembled standard-supply transformer unit is shown in figure 8.

3.3 System Configuration

3.3.1 Electrical Configuration

The configurations of figures 4 and 6 are mandatory, i.e., the standard divider is always connected to the "S" terminal of the voltage comparator. This is necessary because the IVD (T4) input impedance is somewhat low relative to the standard divider output impedance (the order of 1 MΩ vs 2 kΩ). This results in significant (and voltage-variable) loading of the divider if T4 is connected to it. On the other hand, T4 does not load standard transformer T2 or the CCVT output significantly. This mandatory configuration establishes the constraints on standard divider ratio discussed earlier. In other words, if $\rho_T/\rho_S > 1.11 \ldots$, the comparator connection cannot be reversed to compensate for it.

3.3.2 Physical Configuration

The NBS system is "grafted" onto the prototype, i.e., the supply-standard transformer module (T1-T2) is installed permanently in the prototype system truck, together with its low-voltage, variable autotransformer power supply (see fig. 2). Interlocks prevent the system from being energized when someone is in the power compartment.

The standard divider is, of course, part of the prototype system. The voltage comparator is independent and can be set up anywhere that 120-V, 60-Hz power is available. In the field, it is normally placed in the back of a van or on the tailgate of a station wagon, close to the calibration truck.

This configuration not only provides economy of hardware, but is extremely convenient in testing the system. Testing consists primarily of operating the simplified system, either in tandem or in parallel with the prototype system in calibrating the same group of CCVTs.

A stand-alone system could easily be housed in a truck similar to the NBS calibration truck. Alternatively, to avoid a dedicated truck, all hardware except the modular divider could be installed in a small van. A non-dedicated truck could then be used to transport the divider to the substation. Going a step further, the comparator and standard transformer could be set up in the control house, avoiding even the necessity for a dedicated van.

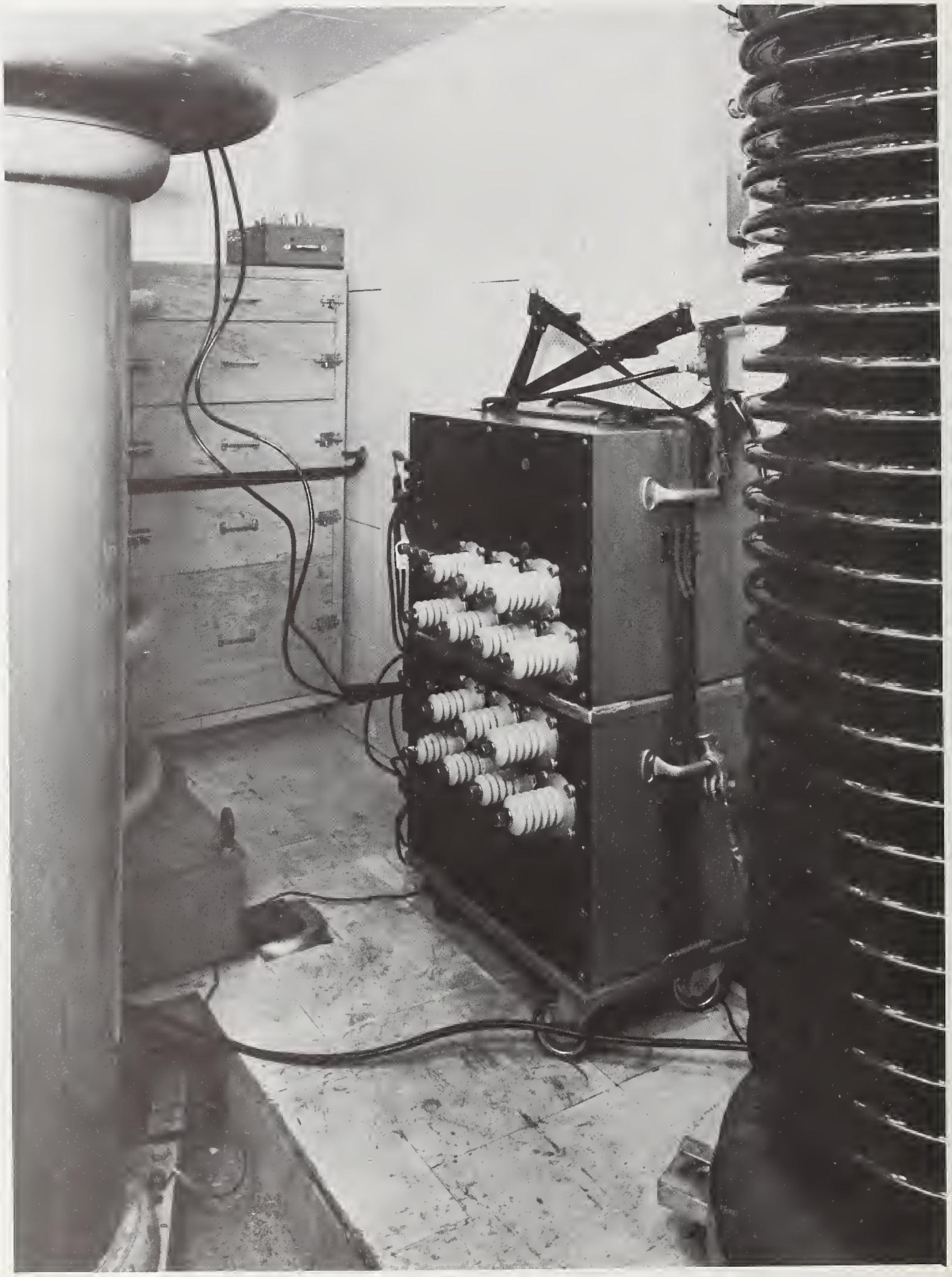

Figure 8. Supply-standard transformer module (T1-T2).

4. SYSTEM EVALUATION

4.1 Overview

The steps taken as part of system evaluation included (1) redetermination of the voltage dependence of the standard divider; (2) calibration of the standard transformer T2; (3) calibration of the voltage comparator, including the IVD (T4) and the quadrature circuit; and, most important, (4) system tests, including actual CCVT calibrations which compared the results with those obtained with the prototype system at the same or proximate time.

Item (1) above was performed in a commercial laboratory, items (2) and (3) at NBS. Item (4) was partially simulated at NBS, but the true evaluation was carried out in utility substations. These tests will now be discussed in detail.

4.2 Voltage Dependence, Transfer Standard Divider

Before the simplified system could even be breadboarded, it was necessary to determine whether the transfer standard divider could be calibrated at the proposed 10-20 kV instead of at the 100 kV used for the prototype, i.e., whether it had a tolerable and reproducible voltage dependence over this wider voltage range. These tests were performed in a commercial high-voltage laboratory using the prototype system as a portable calibration laboratory. A 500-kV laboratory standard capacitor was calibrated with the NBS system, then used as the high-voltage standard in tests on the NBS divider.

The procedure was similar to that used in the initial factory tests of the divider (see section 6-4 and appendix B, [4]). Several series of tests were run in which the voltage was varied up and down between 15 or 20 kV and 300 kV as rapidly as possible, pausing at the end points for at least one minute to allow the ratio value to stabilize. This gave much more reasonable and consistent results than the earlier tests (see specifically, appendix B, fig. B-3, [4]). These stabilized end points were generally repeatable to 10 or 20 ppm. A total of 19 such cycles were run. Treating the results as random, average total voltage dependence was -0.018 percent between 15 and 300 kV, with a scatter (3σ) of about 0.012 percent. A series of voltage dependence curves was also run, with the same hysteresis-type results as were found in the factory tests (appendix B, fig. B-2, [4]). Because more stabilizing time was allowed at the end points than in earlier tests, the results were somewhat more orderly, and tended, in general, to confirm the results of the up-and-down tests above. The divider was thus demonstrated to be suitable for use in the proposed simplified system.

4.3 Standard Transformer T2

This particular transformer is marketed as a laboratory standard, claimed to be within ±0.01 percent of nominal on ratio and within ±0.02 mrad of zero phase angle (at zero burden) at the ratio of interest (14400:120 = 120:1). It was calibrated using the NBS laboratory standard current comparator bridge [8], with the following results: RCF (or F) = 0.99989, or ratio = 119.987:1, and γ = 0.008 mrad. Approximately 10 subsequent calibrations using the prototype system (identical in principle, but less accurate than the laboratory bridge above), including spot checks in the field, have yielded an average RCF of 0.99989 ($\sigma \cong 6 \times 10^{-5}$) and an average phase angle of 0.03 mrad ($\sigma \cong$ 0.03 mrad). Since a sizable part of the above uncertainty is in the prototype system itself, it appears that T2 can safely be used as a field standard, with uncertainties of about ±0.02 percent and ±0.1 mrad, subject only to periodic recalibration in the laboratory.

4.4 Voltage Comparator

4.4.1 Inductive Voltage Divider (IVD) T4

The IVD is the most critical element in the comparator, since it compares the ratio[5] of the standard divider with the ratio of the standard transformer (measurement C3) or the test CCVT (measurement C4). In calibrating the standard divider, the nominal IVD ratio α_{C3} is a small fraction of full scale (e.g., $\alpha_{C3} \cong 120/2500 = 0.048$ for the 500-kV divider configuration, or about 5 percent). Therefore, in order that the IVD introduce no more than 0.01 percent uncertainty into the measurement, its error must not exceed 5% x 0.01% = 5 ppm of full scale.

This particular IVD has been calibrated against NBS standards, and found to have maximum corrections at any dial setting of 0.1 or less, of approximately 0.2 ppm of full scale for ratio and 3 μrad for phase angle. This translates to less than 4 ppm and 60 μrad for the example above. It is expected to maintain this accuracy indefinitely, subject only to periodic reverification.

4.4.2 Quadrature Circuit

As described in detail in appendix A-3, the quadrature circuit selects an accurately known portion of the in-phase output of the IVD, phase shifts it, and further subdivides it for injection in series with the in-phase output. Since the in-phase value is controlled very accurately by the setting of the IVD (see section 4.4.1), the quadrature circuit can, in principle, be calibrated at any setting of the IVD. The simplest and most convenient point is at the 1:1 setting ($\sigma_C \cong 1.0$).

[5]Strictly speaking, only the in-phase portion, but the difference is negligible at the very small phase angles normally encountered here.

A simple circuit for making this calibration is shown in figure 9, where C is an accurately known capacitor, and R is an accurately known variable resistor. Voltage V_2 is compared with voltage V_1. R is varied to obtain phase shift between V_1 and V_2 over the quadrature range of 0-100 mrad. The calculated values of γ_c and ratio correction factor F are then compared with values measured with the comparator

$$\gamma_c = R\omega C \text{ radians} \tag{8}$$

$$F = \frac{1}{(R\omega C)^2 + 1} \quad . \tag{9}$$

Because the phase angles of metering CCVTs should be less than ±4.6 mrad, and are seldom much more than ±10 mrad, accurate γ_c measurement is required only over the range of ±10 mrad. System accuracy tolerance of 0.3 mrad is 3 percent of this, so that the absolute accuracy required of the quadrature test circuit is quite moderate. A simple calculation will show that if R and C in the circuit of figure 9 are known to ±0.25 percent, γ_c may be calculated to an inaccuracy of no more than ±0.1 mrad at 10 mrad. If measured γ_c is out of tolerance, it can be adjusted with a trimmer resistor (see appendix A-3, fig. 13).

If R in figure 9 is reduced to zero, a simple check of the comparator at $\alpha_c \cong 1.0$ and $\gamma_c = \pm 0.00$ can be made. If this check shows α_c to be unity to a few ppm and $\gamma_c = \pm 0.00$ to 10 µrad or so, it is unlikely that anything is seriously wrong with the comparator. This can be valuable as a quick troubleshooting procedure in the field.

4.5 System Tests

4.5.1 Laboratory Tests

The conclusive evaluation of the system consisted of its use in conjunction with the prototype system to calibrate CCVTs in the substation, and the comparison of the two sets of results. Prior to this, preliminary laboratory tests included simultaneous calibrations of the standard divider (measurement C3, simplified system, and measurement 3, prototype system) at 14.4 kV, and simultaneous calibrations of simulated test pieces (measurements 4 and C4) at 100 kV. These tests, performed for the most part with semi-packaged, preliminary configurations of the system, demonstrated its general feasibility. "Simultaneous" above means the current comparator bridge of the prototype system and the voltage comparator of the simplified system were connected in parallel and balanced sequentially (the paralleled systems are not entirely independent of each other). Parallel operation allowed the same stray capacitance (which has a significant effect

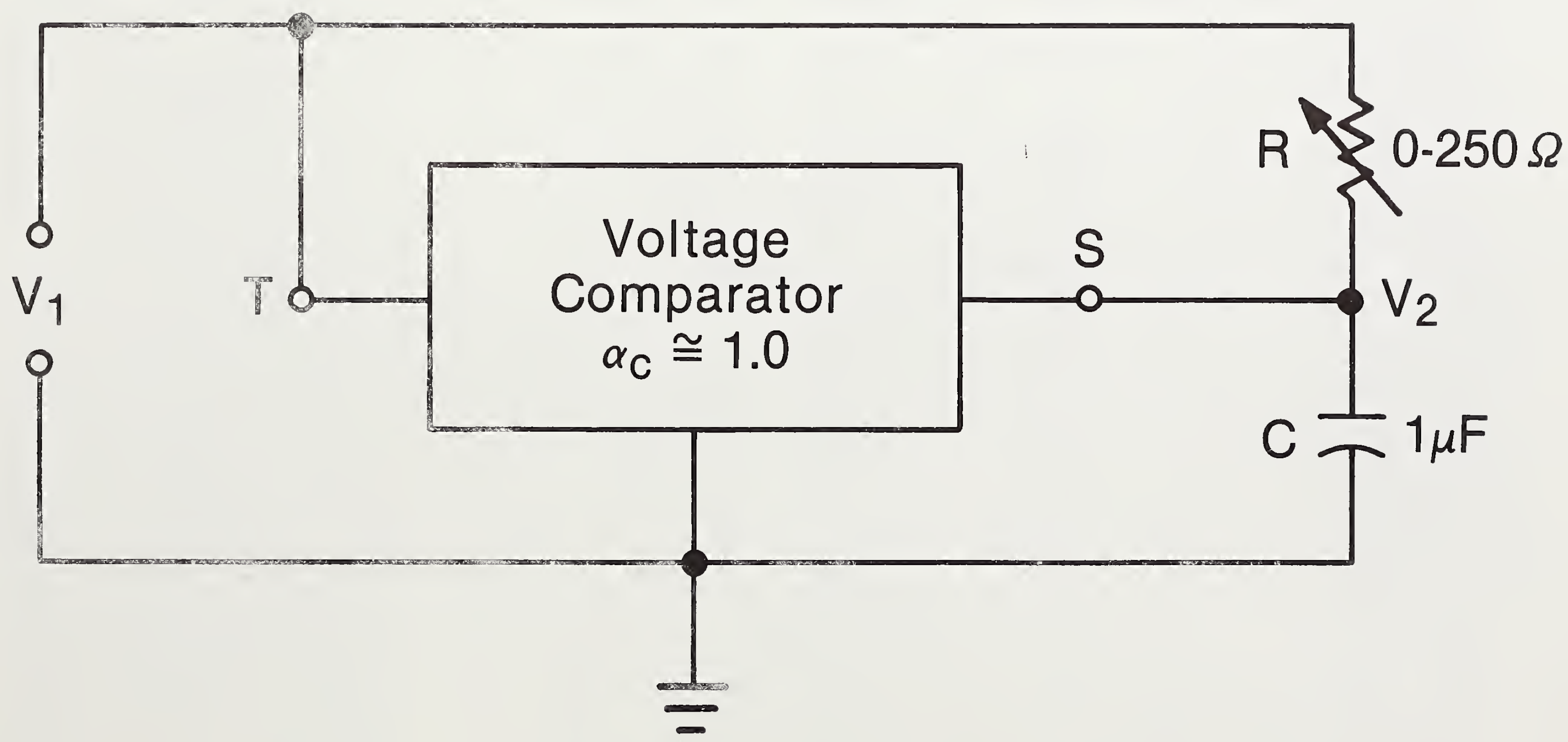

Figure 9. Simple calibration circuit for the voltage comparator quadrature circuit.

on divider ratio) to be presented to the divider low side for both measurements, thus avoiding the necessity for auxiliary capacitance measurements in order to compare results. Difference in stray capacitance is brought about by the presence of a standard capacitor (C_{SM}, fig. 3) and its strays during the current comparator bridge measurement, differing input cable lengths for the two measurements (the effect of which is of the order of 100 ppm/m), and stray capacitance in the detector transformer (T5, fig. 6) during voltage comparator measurements.

In the "simultaneous" mode, laboratory results from the two systems consistently correlated to better than 0.02 percent and 0.1 mrad. For further discussion of these preliminary tests, see [4], section 9, and appendix H.

4.5.2 Field Tests

Two field tests of the simplified system were carried out in conjunction with CCVT calibrations at the 500-kV Juniata Substation of the Pennsylvania Power and Light Co. (PP&L), New Bloomfield, Pennsylvania. The two systems have since been compared extensively in another field calibration.

The first field tests, in October 1979, involved a semi-packaged version of the final system and were intended to demonstrate field feasibility. Initially, the system functioned properly for standard divider calibration (measurement C3), but could not be balanced beyond three places when on-line (measurement C4). It was postulated that excessive third and fifth harmonics in the substation voltage caused the commercial detector to saturate. Substitution of an older, less harmonic-sensitive tube-type wave analyzer for this detector temporarily solved this problem. Results obtained with the simplified system were then found to agree with prototype system results in simultaneous calibration to a few hundredths of a percent and a few tenths of a milliradian. Field feasibility was thus demonstrated in these tests.

In the interim between the first and second field tests, the detector saturation problem alluded to above was investigated in the laboratory. A circuit was set up to introduce excess harmonics into the input of the detector. This produced the saturation effect observed in the field. A 60-Hz bandpass filter was designed, consisting of a twin-T network in the feedback loop of an operational amplifier. Placing this filter ahead of the detector solved the problem. A detailed discussion of the twin-T filter network is found in appendix A-4.

The second field test was performed in May 1980 at the same PP&L substation. Calibrations of 12 CCVTs allowed comparison of the results from 30 measurements (more than one tap per device) with prototype system results (measurements 4 and C4). These results are plotted in figure 10, in which the prototype system values are taken as reference (the origin). The mean difference between systems for 30 data points was approximately 230 ppm and 0.05 mrad, with standard deviations of 190 ppm and 0.17 mrad, respectively.

The new system has since been used extensively in conjunction with the prototype in field tests involving 24 CCVTs at two other substations. The comparison of nearly 60 data points is plotted in figure 11. Results are seen to be quite similar - a mean difference between systems of approximately 180 ppm and -0.10 mrad, with standard deviations of 170 ppm and 0.10 mrad. The figure 10 mean and the combined mean are plotted in figure 11 for purposes of comparison.

4.5.3 Summary

As figures 10 and 11 show, field comparison with the prototype system shows mean agreement to better than 0.025 percent (250 ppm) and 0.1 mrad. This is considerably better than the apparent uncertainty of the comparisons ($3\sigma_F \cong 0.05$ percent, $3\ \sigma_\gamma \cong 0.4$ mrad). Since the prototype system is believed to have uncertainties of about ±0.1 percent and ±0.3 mrad, ±0.2 percent and ±0.6 mrad is believed to be a reasonable assessment of the overall accuracy of the simplified system.

The above conclusion is reinforced by an error analysis based on the components of the simplified system. This analysis, for ratio correction factor only, is summarized in table 1, and shows an expected uncertainty of about ±0.06 percent, somewhat larger than the intercomparison uncertainty above. This should not be surprising since the major sources of uncertainty, the standard divider and the detector null bias, are common to both systems. A similar analysis for phase angle, not shown, shows the expected uncertainty to be well within the above numbers for phase angle.

5. SUMMARY AND CONCLUSIONS

A simplified system for field calibration of CCVTs has been developed and field tested. It is estimated to have an inaccuracy less than ±0.1 percent and ±0.6 mrad for ratio correction factor (F) and phase angle (γ), respectively, at 500 kV. This is comparable to the prototype system against which it was evaluated, and which it could replace.

The system has only three major components: a modular capacitive transfer standard divider, a combined supply and standard transformer, and a cabinet-mounted voltage comparator. By comparison, the prototype system has five major components. Its mass (with 500-kV divider) is about 1600 kg, versus 2250 kg for the prototype system.

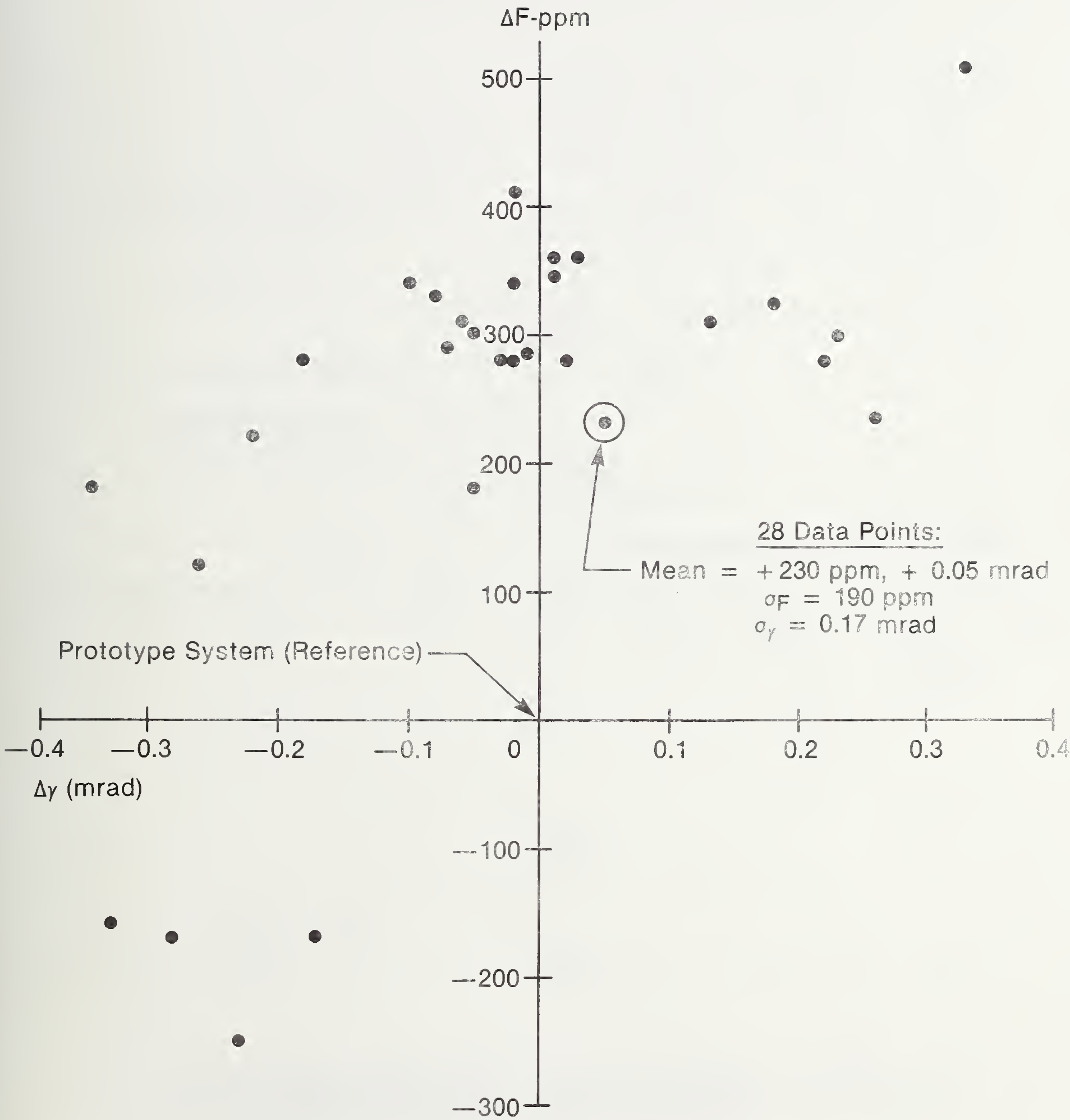

Figure 10. Deviation of simplified system results from prototype system results, field calibration of CCVTs, May 1980.

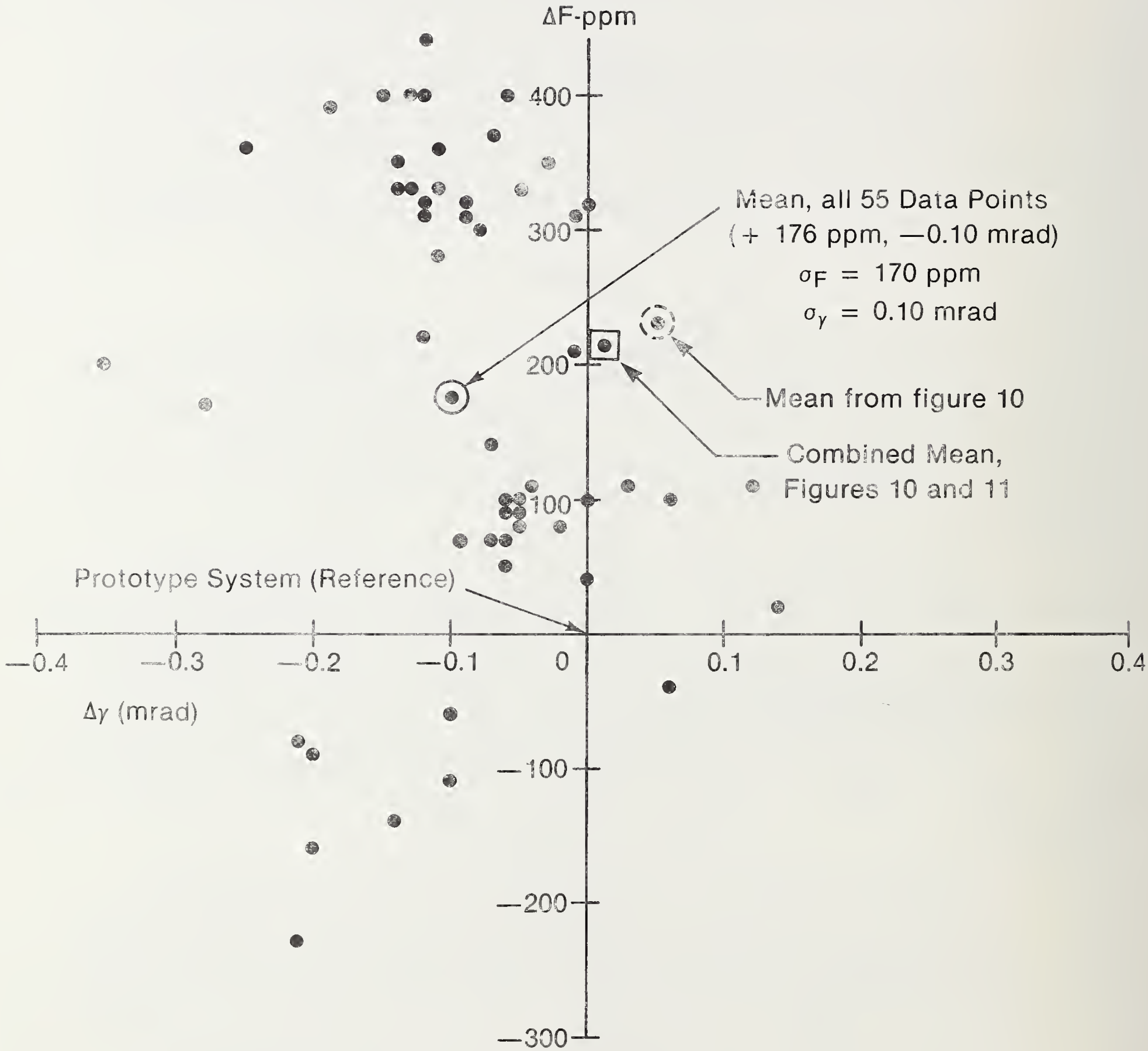

Figure 11. Deviation of simplified system results from prototype system results, field calibration of CCVTS, October 1980.

Table 1. Summary of error and fixed correction estimates, simplified field calibration system for CCVTs

Sources of Errors	Fixed Corrections Percent	Uncertainties $n^{(1)}$ Percent	n^2	(2) Mult	$n^2 x$ Mult
1. Standard Transformer	0	±0.01	10^{-4}	2	2×10^{-4}
2. Voltage Comparator	0	±0.005	0.25×10^{-4}	3	0.75×10^{-4}
3. Detector (Null Bias)	0	±0.02	4×10^{-4}	3	12×10^{-4}
4. Modular Standard Divider:					
a. Voltage Dependence (15-300 kV)	-0.02	±0.02	4×10^{-4}	1	4×10^{-4}
b. Proximity Effects	-0.01	±0.015	2.25×10^{-4}	1	2.25×10^{-4}
c. Temperature Effects	0	±0.015	2.25×10^{-4}	1	2.25×10^{-4}
d. Miscellaneous	0	±0.015	2.25×10^{-4}	3	6.75×10^{-4}
5. Ground Voltages	0	±0.010	10^{-4}	1	10^{-4}
$\sum$(Fixed Corrections)	-0.03				
$\sum n^2$					31×10^{-4}
$(\sum n^2)^{1/2} = 3\sigma$					0.056
Total Estimated Random Error - Percent					0.056

$^{(1)} n = 3\sigma$

(2) Number of times the component is used in the entire calibration, e.g., the voltage comparator is used in meas. C3, meas. C4, and meas. C3 repeat, or three times.

Although, as explained earlier, the new system is "grafted" onto the older system, this is a matter of operational convenience. Standing alone, the system could dispense with the dedicated truck. The standard transformer, voltage comparator, and smaller accessories could be transported in, and operated from, a medium-sized van (not necessarily dedicated). The disassembled modular divider would require a medium-sized, non-dedicated truck. With proper attention to weather, this could be an open truck, although it would be necessary to protect the porcelain modules from flying stones and other road hazards. If dedicated vehicles can be dispensed with, the cost of replicating such a system should be substantially less than for the prototype.

The calibration process itself is simpler, involving two measurement steps instead of three. It also appears feasible to make the logistics much simpler, e.g., the standard transformer and voltage comparator might be set up in the control house, freeing the calibration van and permitting easy access to the CCVT test points.

Two disadvantages, neither very serious, appear to be associated with the simplified system. The first is that the standard divider modules cannot be tested at 100 kV (measurement 1, fig. 3). This is a procedure of somewhat marginal utility, although it affords some protection against catastrophic failure of the divider when it is connected to the bus. Periodic over-voltage testing in the laboratory should be almost as useful. The second disadvantage is that the standard divider is calibrated at only 14.4 kV (measurement C3) versus 100 kV (measurement 3) for the prototype. This results in a 7:1 reduction in detector sensitivity. The lowered sensitivity increases the vulnerability to noise (see, particularly item 3, table 1), and puts more stress on the necessity to evaluate the voltage dependence of the standard divider (section 4.2). Standard transformers are available at ratings up to 35 kV. Their use would increase sensitivity above by 2.5:1, and should be considered in any reproduction of the present system.

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APPENDIX A

SIMPLIFIED SYSTEM COMPONENT DETAILS

1. INTRODUCTION

Elementary circuit diagrams of the complete system are shown in figure 4; an elementary diagram of the standard divider is shown in figure 5, and of the voltage comparator in figure 6. These are combined for ease of reference in figure 12, in the configuration for standard divider calibration (measurement C3, fig. 4(a)). Transformer T1 applies 14.4 kV (V_1) to T2 and to the standard divider.

2. DERIVATION OF SYSTEM EQUATIONS

2.1 Standard Divider Calibration

Balance for the in-phase quantity is obtained by adjusting the IVD ratio setting α_{C3}, and for the quadrature quantity by adjusting the $j\gamma_{C3}$ output of the quadrature circuit. Balance is indicated by a zero reading on the null detector. Then, from figure 12, the exact equation of balance is

$$V_S = V_A (1 + j\gamma_{C3}) = \alpha_{C3} V_T (1 + j\gamma_{C3}) \qquad \text{(A1) and (7)}$$

where $V_A = \alpha_{C3} V_T$, γ_{C3} is the calculated fraction of V_A operated on by the quadrature circuit, and V_S and V_T are the output voltages of the standard divider and the standard transformer, respectively. The quantity of interest in eq (A1) is V_S/V_T, which strictly speaking equals α_{C3} $(1 + j\gamma_{C3})$ and has a magnitude larger than α_{C3}. However, for the small phase angles ($\gamma \leq 10$ mrad) normally encountered in CCVT calibration, it is easy to show that α_{C3} equals the magnitude of V_S/V_T to within $(\gamma_{C3})^2/2$ (50 ppm for γ_{C3} = 10 mrad, less for γ_{C3} <10 mrad). Therefore, we may state that

$$\left| V_S/V_T \right| = \alpha_{C3} \quad . \qquad \text{(A2)}$$

The quantity of interest in figure 12 is the ratio ρ_S of the standard divider. But $\rho_S \equiv V_1/V_S$, and the standard transformer ratio $\rho_T \equiv V_1/V_T$. Substituting these values in (A2) and solving for ρ_S, we obtain

$$\rho_S = \rho_T/\alpha_{C3} \quad . \qquad \text{(A3) and (3)}$$

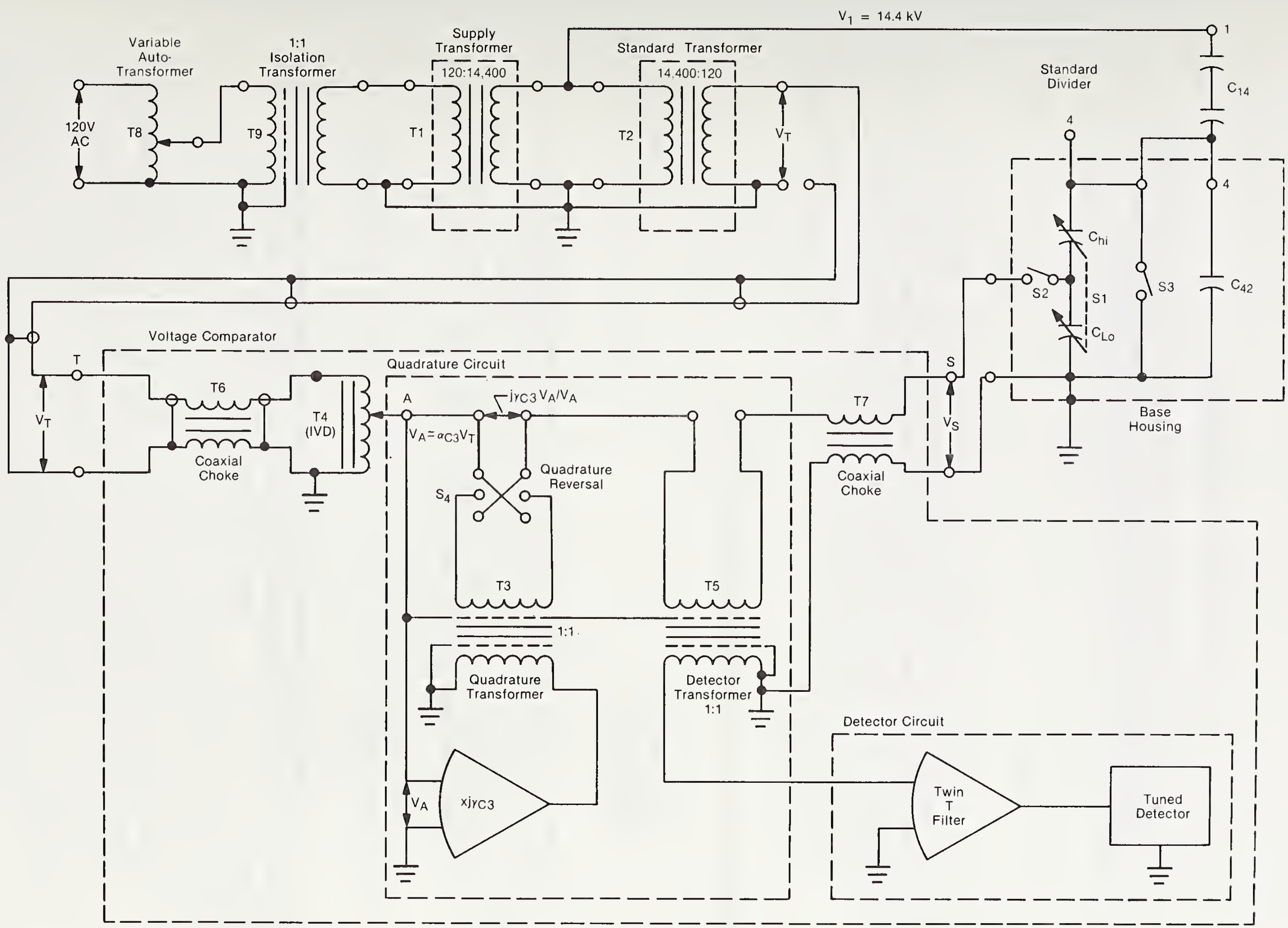


Figure 12. Basic circuit of complete simplified system for field calibration of CCVTs.

2.2 CCVT Calibration

Replacing standard transformer T2 in figure 12 with the test CCVT, thereby substituting V'_A, α_{c4}, V_t, ρ_t, and γ_{c4} for the corresponding terms above, identical reasoning produces

$$\rho_s = \rho_t/\alpha_{c4} \tag{A4}$$

where the subscript t denotes "test piece," and the subscript 4 denotes "measurement C4." Applying the ANSI definition for ratio correction factor ($F_t \equiv \rho_t/\rho_{tN}$), where ρ_{tN} equals the nominal ratio of the test CCVT, e.g., 2500:1 for a 500-kV metering tap

$$\rho_s = F_t\ \rho_{tN}/\alpha_{c4}\ . \tag{A5}$$

Equating (A3) and (A5) and solving for F_t,

$$F_t = \left(\frac{\rho_T}{\rho_{tN}}\right)\left(\frac{\alpha_{c4}}{\alpha_{c3}}\right)\ . \qquad \text{(A6) and (5)}$$

From (A1), the voltage injected by the quadrature circuit is $j\gamma_{c3}\ V_A = j\gamma_{c3}\ \alpha_{c3}V_T$. The corresponding phase angle is $\tan^{-1}(\gamma_{c3}\ V_A)/V_A = \tan^{-1}\gamma_{c3} \cong \gamma_{c3}$ for small phase angles. γ_{c3} is the algebraic difference of the phase angles of the standard divider (γ_S) and the standard transformer (γ_T). Therefore, $\gamma_{c3} \equiv \gamma_S - \gamma_T$, or

$$\gamma_S = \gamma_{c3} + \gamma_T\ . \qquad \text{(A7) and (4)}$$

Noting that the standard divider stays on the same side of the comparator for both measurements C3 and C4, identical reasoning produces $\gamma_S = \gamma_{c4} + \gamma_t$. Substituting for γ_S in (A7), we have finally

$$\gamma_t = \gamma_T + \gamma_{c3} - \gamma_{c4}\ . \qquad \text{(A8) and (6)}$$

3. VOLTAGE COMPARATOR QUADRATURE CIRCUIT

A detailed diagram of the quadrature circuit is shown in figure 13. Quadrature voltage is generated as follows: input resistor R_1 and amplifier A1's feedback resistor R_{DF} operate as an active voltage divider, producing

$$V_H = -V_A\,(R_{DF}/R_1) \tag{A9}$$

which is a voltage 180° out of phase with $V_A(= \alpha_{C3}V_T)$. R_{DF} is an accurate, highly linear 10-turn helical potentiometer, connected as a rheostat, and controlled by the quadrature balance dial. Its range is 0-10 percent of V_A, equivalent to 0-100 mrad. Operational amplifier A2, resistor R_2, and capacitor C_1 form a phase shifting network to generate voltage

$$V_M = V_H\left(\frac{-jX_{C1}}{R_2}\right). \tag{A10}$$

Substituting V_H from (A9)

$$V_M = jV_A\left(\frac{R_{DF}}{R_1}\right)\left(\frac{X_{C1}}{R_2}\right). \tag{A11}$$

R_2 can be adjusted to make $|V_M| = |V_H|$, i.e., $|R_2| = |X_{C1}|$. R_9 through R_{12} are precision resistors forming a four-ratio voltage divider providing quadrature ranges of 10, 20, 50, and 100 mrad. After passing through buffer amplifier A3 and surge buffer resistor R_8, this voltage is injected into 1:1 quadrature transformer T3, which introduces it into the balance circuit. $R_{DF}/R_1 = \gamma_{C3}$, and by selecting the maximum value of R_{DF}/R_1 to be equal to 0.1, the quadrature dial is made to read directly in milliradians.

Precision components (0.1 percent or better) are starred. Components not discussed comprise conventional operational amplifier configurations for stabilization, dc blocking, surge protection, etc. The operational amplifiers are off-the-shelf items. Other similar amplifiers could be used. The entire quadrature circuit (except the dc power supply and R_{DF}) plus detector transformer T5 is contained in a single moderate-sized electronic chassis. The dc power supply is mounted outside this chassis in order to reduce 60-Hz pickup by the low-level signal leads inside. T3 and T5 are of NBS construction, wound on high permeability cores, and double screened for complete isolation.

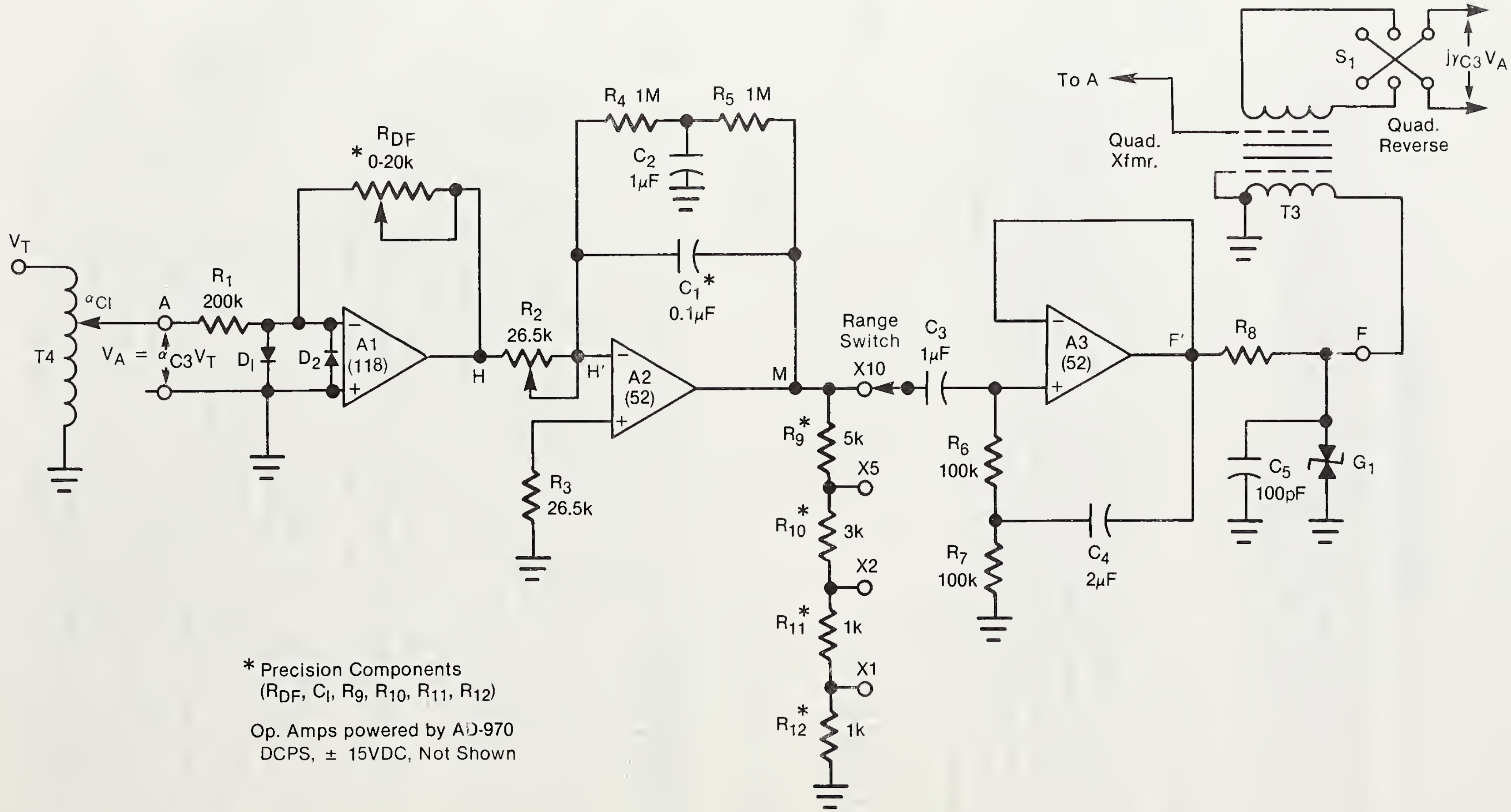


Figure 13. Detailed diagram of voltage comparator quadrature circuit, simplified system.

4. VOLTAGE COMPARATOR DETECTOR CIRCUIT

From figure 12, note that the detector circuit consists of detector transformer T5, in series with the twin-T filter and a commercial tuned detector. As mentioned earlier, T5 is mounted in the quadrature circuit chassis.

Figure 14 shows the detailed circuit of the filter. It consists of a twin-T circuit in the feedback loop of operational amplifier A1. The twin-T consists of two T-networks: a high-pass filter (C_1, C_2, and R_3) and a low-pass filter (R_1, R_2, and C_3). Connected as shown, they form a notch filter (maximum impedance at frequency f_0, and tending toward zero on either side of f_0). Thus when the twin-T circuit is placed in the feedback loop in parallel with R_f, amplifier gain approaches $(-R_f/R_{in})$[6] at f_0, and zero at frequencies far from f_0, and the entire circuit functions as a band-pass filter.

If the components are selected so that $C_1 = C_2 = 0.5\ C_3$, and $R_1 = R_2 = 2R_3$, it can be shown that

$$f_o = \frac{1}{2\pi\ R_1\ C_1} \tag{A12}$$

and that for the values shown in figure 14, $f_0 \cong 60$ Hz. The equivalent impedance of the filter in parallel with R_f is

$$Z_\beta = \frac{2R_1(1 + j\omega R_1 C_1)}{1 - (\omega R_1 C_1)^2} \tag{A13}$$

and the overall gain of the filter circuit is

$$V_o/V_{in} = -\left(\frac{R_f}{R_{in}}\right)\left(\frac{Z_\beta}{Z_\beta + R_f}\right) . \tag{A14}$$

From eq (A12), note that $\omega_0 R_1 C_1 = 1$. Then from eq (A13), at f_0, $Z_\beta = \infty$, from which eq (A14) tells us that circuit gain at

[6] R_{in} equals the approximate equivalent delta impedance of the R_8, R_9, and R_{11} (gain potentiometer) T-network, ignoring R_{10}.

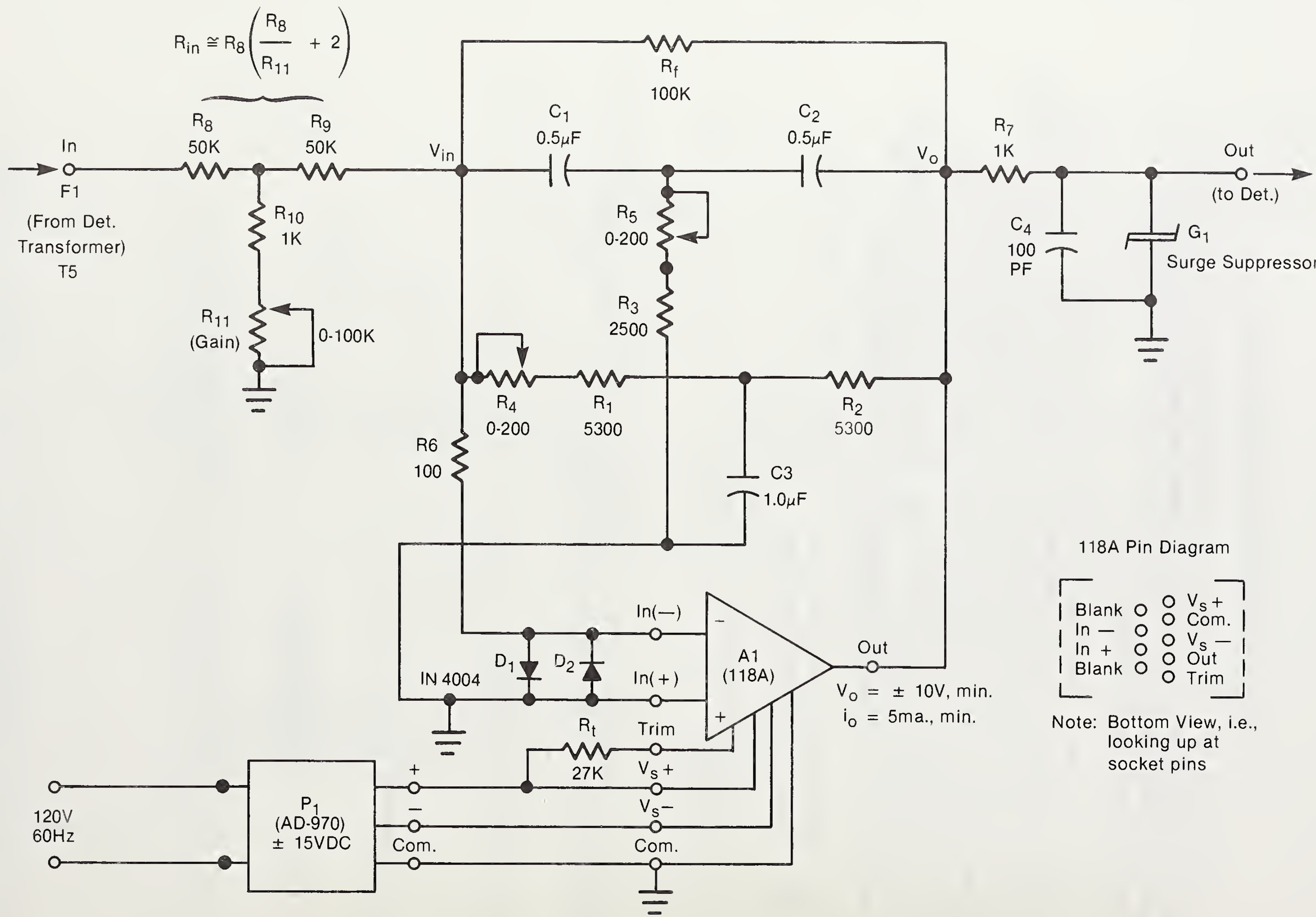


Figure 14. Detailed circuit diagram of twin-T filter for voltage comparator detector, simplified system.

f_o is $(-R_f/R_{in})$, as stated earlier. As f (i.e., ω) approaches zero, Z_β approaches $2R_1$; as f increases beyond f_o, Z_β approaches zero. The latter condition is the important one, since it is 60-Hz harmonics (specifically the 3rd and the 5th) that must be suppressed.

The efficiency with which this is accomplished, i.e., the sharpness of the 60-Hz bandpass, is determined by the matching of the six twin-T components. As a practical matter, the capacitors are first matched as closely as possible, as are the resistors. Then final adjustment is performed using trimmer resistors R_4 and R_5. Perfect tuning need not be obtained because of the inherently narrow bandwidth of the filter, plus the fact that the frequencies to be suppressed are far away from 60 Hz (180 and 300 Hz). The adjusted circuit of figure 14 has a maximum gain somewhat less than unity (gain is not critical, since the detector is highly sensitive at the signal levels encountered), and a bandwidth of about 4 Hz, so that 180 and 300 Hz are down about 30 and 35 dB, respectively. More important than tuning to peak output at 60 Hz is adjustment to make certain the net feedback current of the twin-T filter is not positive, or if it is, that it remains less than the negative feedback current through R_f. Failure to do this will result in operational amplifier instability and saturation.

As implied by the preceding discussion, the six twin-T components should be quite stable and closely matched, and have small temperature coefficients. The other components are non-critical. Gain potentiometer R_{11} is the only front panel control. The power supply is energized when the comparator is plugged in.

The twin-T filter, except for its dc power supply, is mounted in its own chassis. The power supply is external, to reduce 60-Hz interference in the filter circuit.

5. CAPACITIVE TRANSFER STANDARD DIVIDER

The circuit diagram of the capacitive transfer standard divider, with the auxiliary divider shown in detail, is presented in figure 15. Most of the other divider elements are discussed in detail in [4]. The auxiliary divider reduces the nominal 1 kV present at terminal 4 of the main divider to form nominal ratios of 2500:1 and 4500:1 (for a three-module, 500-kV divider), and 3750:1 (for a five-module, 765-kV divider - 2250:1 for a three-module divider). It is composed of computer grade, metallized polycarbonate capacitors, selected for their high stability and small voltage and temperature dependence. The three-microfarad (3 μF) capacitors are rated at 200 V dc. All other individual capacitors are rated at 400 V dc. They are grouped in various series, parallel or series-parallel combinations, in order to obtain the desired net values using readily available sizes and voltage ratings. For example, C_{h2} contains

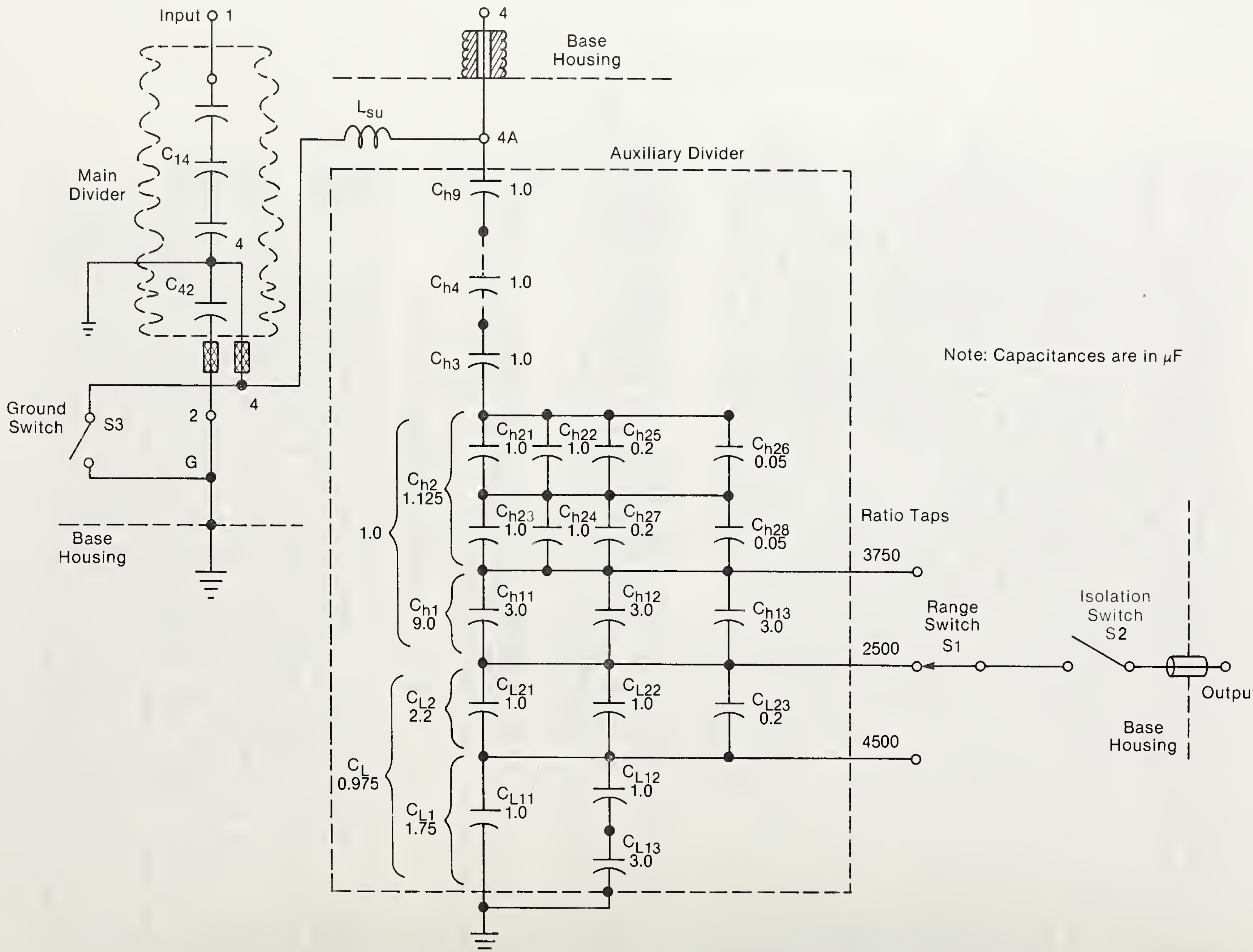


Figure 15. Standard divider circuit, showing details of auxiliary divider.

series-paralleled 1.0, 0.2, and 0.5 μF units, so configured in order to obtain an 800-V rating for C_{h2}. Similarly (not shown in fig. 15), C_{h3} through C_{h9} are each made up of four 1.0 μF, 400-V units in series-parallel, to obtain an 800-V rating.

The entire divider has a dc voltage rating of 8400 V based on the individual capacitors. This is about six times the steady-state requirement (1 kV x $\sqrt{2}$), but is necessary in order for the divider to withstand the surges generated when it is switched on and off the substation bus. These transients, at frequencies of the order of 0.5 MHz, can have values up to 10 or more times the steady-state peak voltage.

At surge frequencies, the series inductance of leads and components largely determines voltage distribution. The design objective, therefore, is to make the inductance of the auxiliary divider as low as possible relative to that of the stack and its series leads. To this end, switch S3 brings terminal 4 of the main divider to ground by a short, direct path. For additional protection, part of the lead between terminals 4 and 4A is coiled to form an inductor, L_{su} ($\cong$ 8 μH). This further subdivides any residual surge voltage appearing at terminal 4. The 60-Hz impedance of L_{su} is negligible relative to the auxiliary divider impedance. Low-voltage step response tests have shown that this configuration reduces the surge voltage across the auxiliary divider by a factor of four to six. This brings it within the dc design values.

The auxiliary divider is contained in an electronic chassis, mounted on the door of the main divider base housing. Terminal 4A and the output terminals are brought out of the chassis on high-voltage bushings. Individual capacitors are mounted on terminal boards supported on high-voltage standoffs. Layout is arranged so as to reduce effective series inductance as much as possible.

6. COAXIAL CHOKES (GROUND VOLTAGE COMPENSATION)

Ground voltage is the difference in potential between two separated points in the substation ground grid. Its typical range is 0.1-0.6 V. If not accounted for, this represents 0.08 to 0.5 percent, or 0.8 to 5 mrad of error based on 115 V. The sources of ground voltage may be clarified by reference to figure 16, which shows the CCVT calibration circuit in the substation. For reasons of safety, there are three grounds in this measurement system (G1, G2, and G3 - G4 is associated with the CCVT). These are connected to the substation ground grid. Currents flowing in the ground grid due, e.g., to unbalanced phase voltages, generate voltages $i_{g1}Z_{g1}$, $i_{g2}Z_{g2}$, and $i_{g3}Z_{g3}$ between these ground points. In addition, magnetic coupling from bus current I or from ground currents, represented

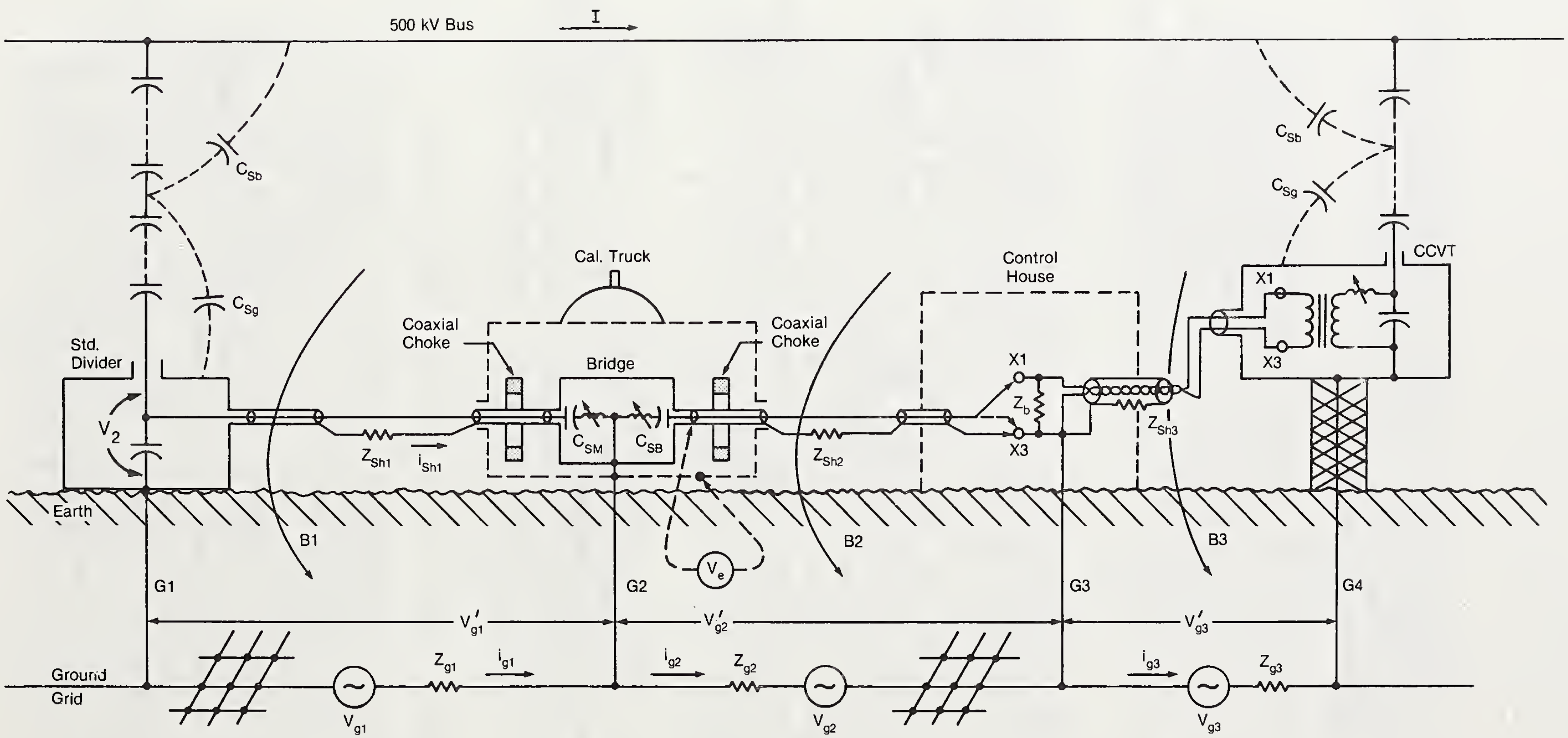


Figure 16. Origin of ground voltages in the field calibration of CCVTs.

by B1, B2, and B3, may induce voltages in these ground loops. The summations of these voltages can be represented by ground voltages, V_{g1}, V_{g2}, and V_{g3}. Considering the NBS system only, and assuming for the moment that there are no coaxial chokes, V'_{g1} is impressed across the standard divider cable shield, and generates an error voltge, $V_{e1} \cong Z_{sh} i_{sh1}$, directly in series with the voltage to be measured (V_2). A similar effect occurs in the control house loop.

The ground voltage effect and its compensation by a coaxial choke can be seen in figure 17. Figure 17(a) shows the ground loop circuit in the absence of the choke. Error voltage, $V_e \cong V_g$, as stated below the circuit diagram, since the cable center conductor is connected to V_g through an impedance approaching infinity ($i_\ell \cong o$).

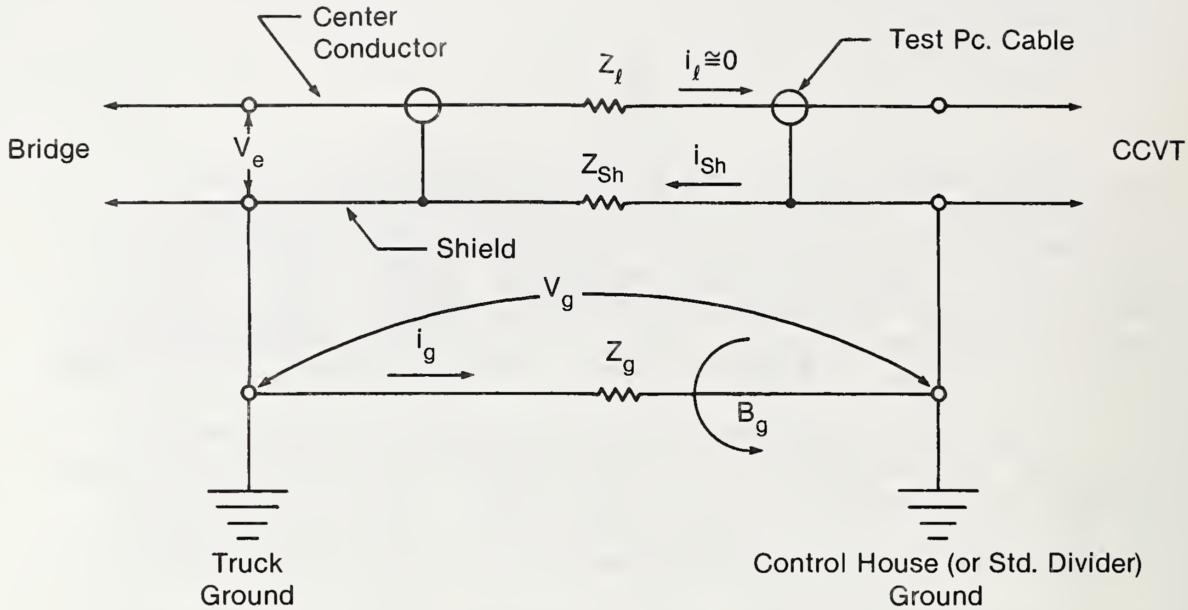
Figure 17(b) shows the same circuit with the coaxial choke in place. The choke is a 1:1 transformer, formed by winding a number of turns of the signal cable on a high permeability toroidal core. Assume that its magnetizing impedance is Z_L; the winding resistance and leakage reactance add to Z_{sh}. Thus any voltage, V_{ch}, appearing across the shield conductor of the choke, also appears in the center conductor portion (diminished only slightly by the combined effect of Z_{sh} and the finite value of Z_L), and in opposition. There is a net error voltage, but since the choke can readily be designed so that $Z_L \geqslant 50\ Z_{sh}$, V'_e is easily reduced to 1 or 2 percent of V_g. Thus if V_g, uncompensated, is 0.5 percent of measured voltage, V_g, compensated, is $\leqslant 0.5/50 = 0.01$ percent.

Since the coaxial chokes are designed specifically to eliminate V_g as an error source, V_g can appear only if these chokes fail to function. Only three such failure modes are admissible: (1) core saturation, (2) grounded cable shield, and (3) open cable shield.

(1) Core Saturation - This occurs when V_g exceeds the choke design voltage. It can be dismissed here, since the chokes were designed and tested for ground voltages up to 2 V, whereas the largest V_g we have seen in practice has been less than 1 V.

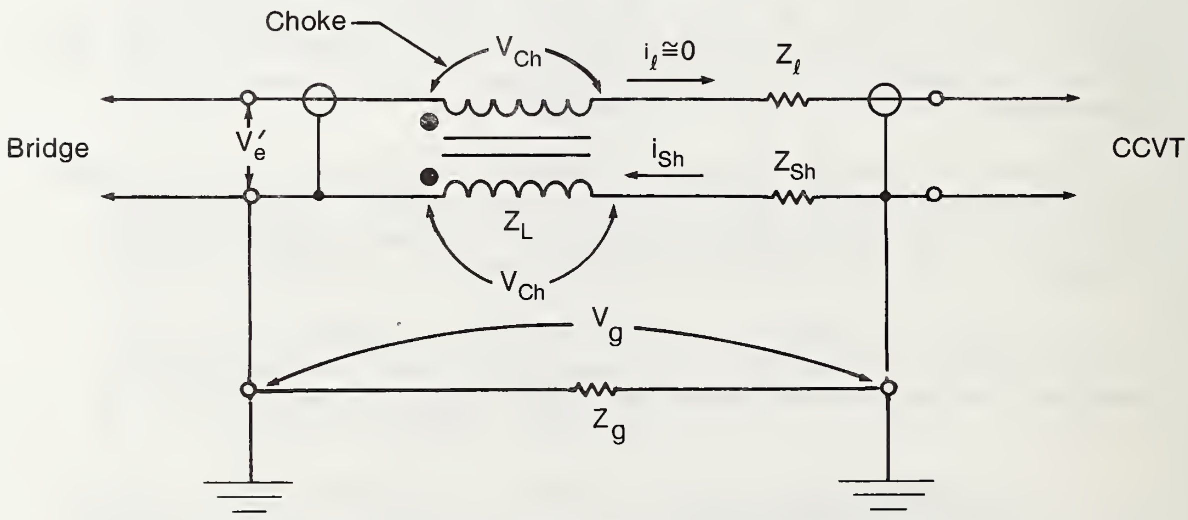
(2) Grounded Cable Shield - Referring to figure 17(b), a signal cable shield shorted to ground ahead of the choke, in the direction of i_{sh} flow, effectively bypasses the choke, returning the circuit to figure 17(a). This can occur, e.g., if an uninsulated cable joint touches wet earth, or if the shield insulation at the truck entrance breaks down.

(3) Open Cable Shield - Referring again to figure 17(b), an open cable shield means $Z_{sh} \to \infty$. From the associated equation, note that in this case $V'_e \to V_g$. An open shield is the limit of a sub-category - bad shield connections. In the latter case, Z_{sh} need only approach or exceed Z_L (typically 50 to 100 Ω) for most of the compensation



$$V_e = i_{Sh}Z_{Sh} + i_\ell Z_\ell \cong V_g$$

a. Without Coaxial Choke:



$$V_e' = V_g\left(\frac{Z_{Sh}}{Z_{Sh} + Z_L}\right)$$

$$\cong V_g(Z_{Sh}/Z_L)\text{, Since } Z_L >> Z_{Sh}$$

b. With Coaxial Choke:

Figure 17. Function of coaxial chokes in eliminating ground voltages.

to be lost. This condition can occur if a shield is broken or intermittent, or if there is a poor connection to neutral in the control house.

The field procedure for ascertaining that the coaxial chokes are functioning properly is illustrated in figure 18, as applied to the truck-control house loop. It involves two simple voltage measurements (DVM, fig. 18), as outlined in the following steps:

(1) Make the voltage measurement shown in the figure (points A-A connected). In a properly designed choke, $Z_L >> Z_{sh}$, so that most of V_g appears across Z_L and is transformed 1:1 into the center conductor, so that

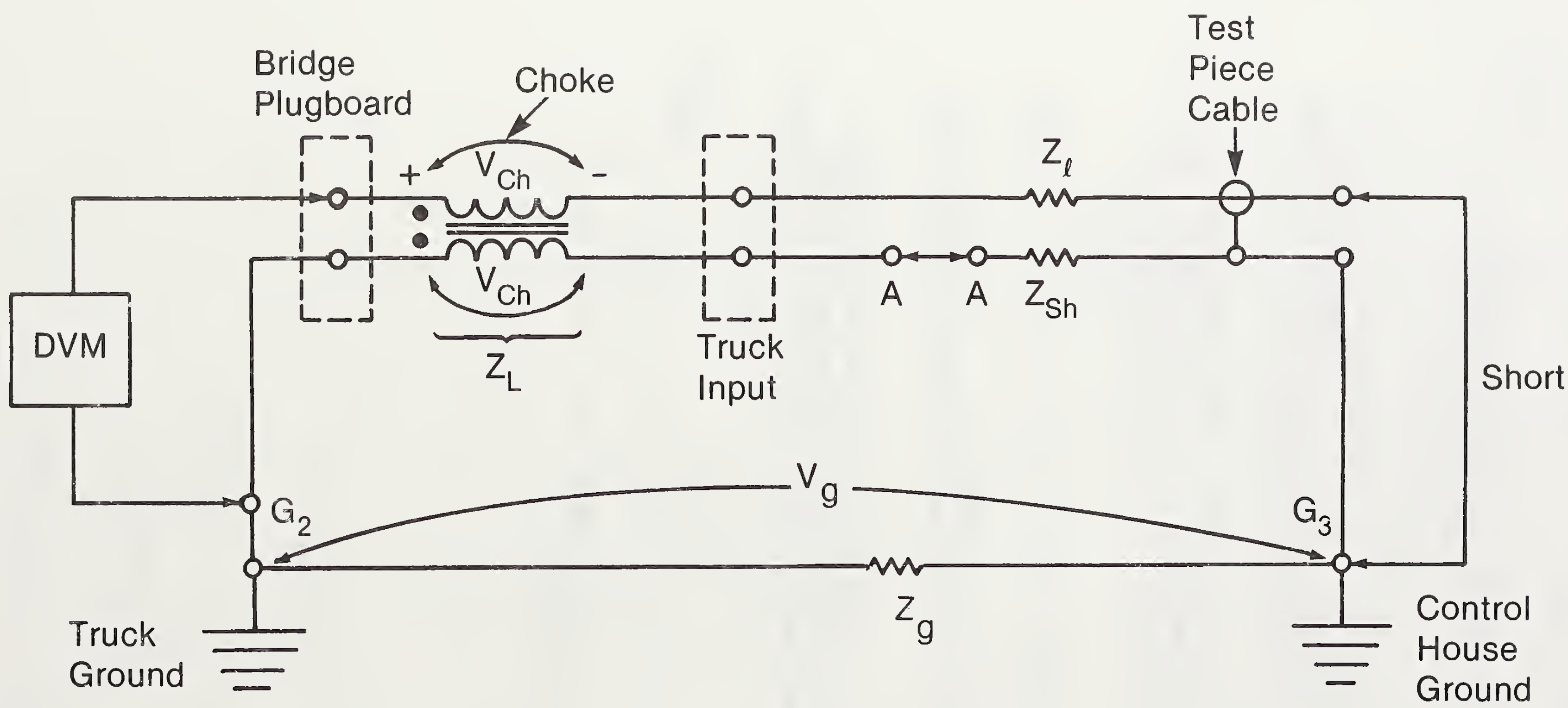
$$V_{DVM} = V_g\ (Z_{sh}/Z_L) = V_e \cong 0 \qquad \text{(A15)}$$

where V_e is the residual error voltage, and is normally <10 mV if the choke is functioning.

(2) In the same circuit, repeat step 1 with the shield broken, e.g., at A-A. Now, no current flows through the choke, the center conductor becomes a drop lead, and the DVM is effectively across G_2-G_3. Therefore,

$$V_{DVM} \simeq V_g\ . \qquad \text{(A16)}$$

If the conditions stated in eqs (A15) and (A16) are satisfied, the coaxial choke is functioning correctly.



Z_ℓ = Center Conductor Impedence
Z_{Sh} = Shield Impedence
Z_L = Coaxial Choke Magnetizing Impedence

Figure 18. Coaxial choke test.

APPENDIX B

A SAMPLE CCVT CALIBRATION PROCEDURE

1. CALIBRATE TRANSFER STANDARD DIVIDER (MEASUREMENT C3)

1.1 Connect the circuit as shown in figure 19.

1.2 Turn on the dc power supply for the voltage comparator quadrature circuit.

1.3 Turn on the detector (battery powered), adjust to low gain.

1.4 Turn on the twin-T filter preceding the detector (ac powered).

1.5 Turn on the variable autotransformer power supply for the standard transformer, inject 10-20 V.

1.6 Obtain a preliminary comparator balance by alternately adjusting first the IVD and then the quadrature circuit for detector minimum (increase detector gain as balance is approached).

Note: Before full balance is obtained tune the detector for maximum output (60 Hz).

1.7 Once a preliminary balance is obtained, increase the input voltage to 120 V (yielding an output of 14 400 V, since the standard transformer ratio is 120:1).

1.8 Obtain a final detector balance, using the technique described in 1.6 (final balance consists of six places on the IVD).

1.9 Record the result. For example, hypothetical values might be

$$\alpha_{C3} = \text{IVD ratio} = 0.047621,$$

$$\gamma_{C3} = \text{phase angle} = 2.60 \text{ mrad}.$$

2. CALIBRATE CCVT (MEASUREMENT C4)

2.1 After the standard divider has been connected to the bus, reconnect the circuit as shown in figure 20.

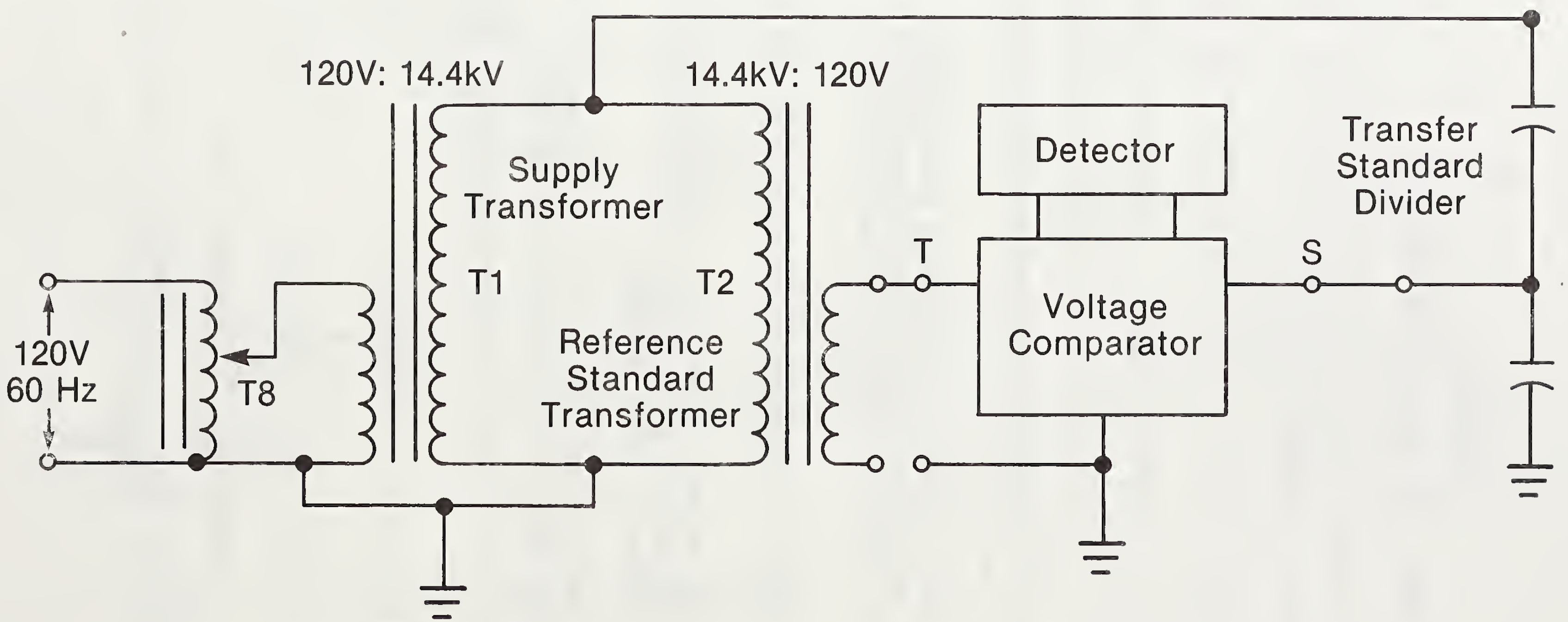


Figure 19. Measurement C3 - calibration of transfer standard divider.

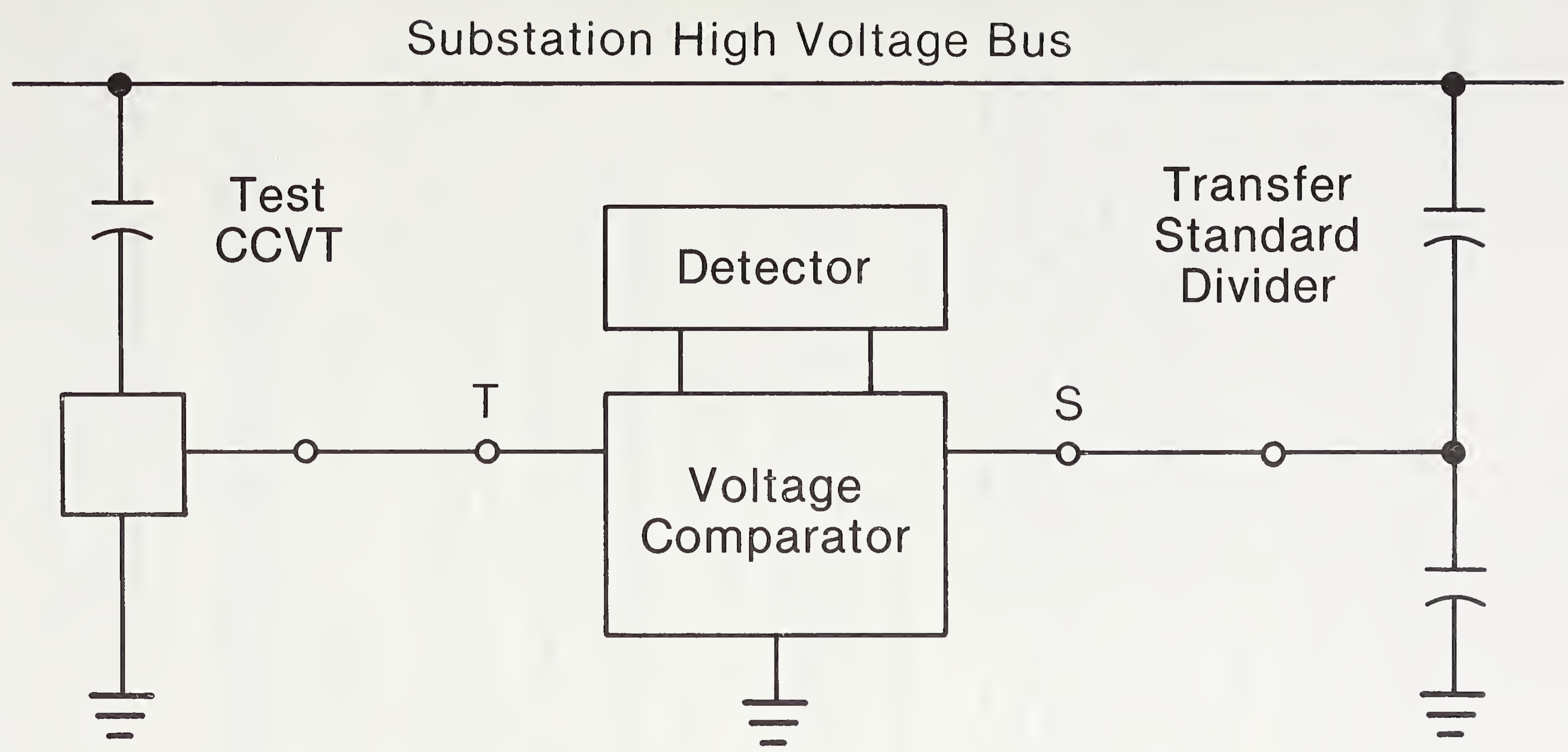


Figure 20. Measurement C4 - calibration of CCVT.

2.2 Repeat steps 1.3 thru 1.9, above (skip 1.7 since transformer T2 is not used). Hypothetical values might be

$$\alpha_{c4} = \text{IVD ratio} = 1.00007,$$

$$\gamma_{c4} = \text{phase angle} = -7.47 \text{ mrad}.$$

3. CALCULATE RESULTS

The ANSI Standard values reported and used are ratio correction factor F_t and phase angle γ_t of the test piece, where F_t is the number by which the nominal ratio of the test piece must be multiplied to obtain its true ratio, and γ_t is by convention the angle by which the secondary (low) voltage leads the primary (high) voltage.

3.1 Standard Divider Ratio (ρ_s):

$$\rho_s = \rho_T/\alpha_{c3}$$

where ρ_T = ratio, standard transformer (nominally 120:1), e.g., 119.990.

Then, using the hypothetical numbers from (1.9),

$$\rho_s = 119.990/0.047621 = 2519.69.$$

3.2 Ratio Correction Factor of Test CCVT:

$$F_t = \left(\frac{\rho_T}{\rho_{tN}}\right)\left(\frac{\alpha_{c4}}{\alpha_{c3}}\right).$$

Using hypothetical data from 2.2 and assuming that ρ_{tN} = 2500:1, and ρ_T = 119.990,

$$F_t = (119.990/2500) \times (1.00007/0.047621) = 1.00795.$$

3.3 Phase Angle of Test CCVT:

Very simply, from the conventional definition,

$$\gamma_t = \gamma_{c3} + \gamma_{c4} = (2.60 - 7.47)\ 10^{-3} = -4.87 \text{ mrad.}$$

Thus a report on this CCVT would show $F_t = 1.00795$, and $\gamma_t = -4.87$ mrad, modified by small corrections to the standard divider for voltage dependence, proximity effects, etc. Typically this might be -0.03 percent and +0.2 mrad, respectively, modifying the above values to

$$F_t = 1.00765,$$

$$\gamma_t = -4.67 \text{ mrad.}$$

Note that this hypothetical test piece is out of tolerance on ratio correction factor and marginal on phase angle for metering application, where the corresponding limits are 1.003 and -4.66 mrad, respectively.

4. PRECAUTIONS

4.1 Ground voltage tests - Make certain these are run on the standard divider and test piece at least once each time the divider goes on line. Preferably, they should be checked more often, or even monitored. See appendix A, section 6, for further discussion.

4.2 Signal cables - Use the same standard divider signal cable for both measurements C3 and C4. This cable forms part of C_{10} (fig. 5) and changes the divider ratio by approximately 100 ppm/m of cable length on the 2500:1 tap.

5. SUBSTATION SAFETY

A safety protocol for the prototype system, followed in the substation by NBS, is presented in detail in [11]. Most of the material there is applicable to the simplified system.

6. MISCELLANEOUS

The complete (500-kV) standard divider mass is about 1150 kg (2500 lb) and its height is 5.5 m (18 ft). This much lifting capacity and height must be available for moving the divider. In modular form, the greatest weight and height are 500 kg and 2 m, respectively.

Because it is desirable to set up the comparator and standard transformer reasonably well away from energized buses, signal cable runs of 200 m or more will be common. Heavy duty coaxial cables with UHF connectors, in lengths of 15 m (50 ft) and 30 m (100 ft) are easiest to store and handle, unless a machine-operated reel is available. Cable joints should be insulated from ground (see discussions on ground voltages).

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBS TN 1155	2. Performing Organ. Report No.	3. Publication Date May 1982

4. TITLE AND SUBTITLE

A SIMPLIFIED SYSTEM FOR CALIBRATION OF CCVTs IN THE SUBSTATION

5. AUTHOR(S)

David L. Hillhouse, Oskars Petersons, and Wilbur C. Sze

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

Final

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

Sponsored in part by

Pennsylvania Power and Light Company
Two North Ninth Street
Allentown, PA 18101

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,*

Coupling capacitor voltage transformers (CCVTs) are widely used for the revenue metering of energy exchanged between utilities at EHV (345-500 kV) interties. These devices are installed permanently in substations, and must be calibrated there. Allowable error is ±0.3 percent and ±4.6 mrad (milliradians).

NBS developed, and has had in operation for several years, a prototype system for field calibration of these CCVTs. This prototype system is more accurate, more complicated, more bulky, and more costly than is essential for this application.

This report describes a simplified, lighter, and less costly CCVT calibration system, newly developed and field tested by NBS. The principal elements of this system are a portable reference standard transformer and moderate voltage power supply (14.4 kV), a modular capacitive transfer standard divider, and a voltage comparator. Results obtained with this system agree with the prototype to within ±0.03 percent and ±0.1 mrad.

The prototype system is installed permanently in a dedicated calibration truck. The new system could operate with a non-dedicated truck to transport the disassembled modular divider, and a van to transport the rest of the components and to serve as a field laboratory.

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

CCVTs; EHV revenue metering; energy metering; field calibration; 500 kV; 500 kV substation measurements; metering accuracy CCVTs.

13. AVAILABILITY

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14. NO. OF PRINTED PAGES

57

15. Price

USCOMM-DC 6043-P80

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