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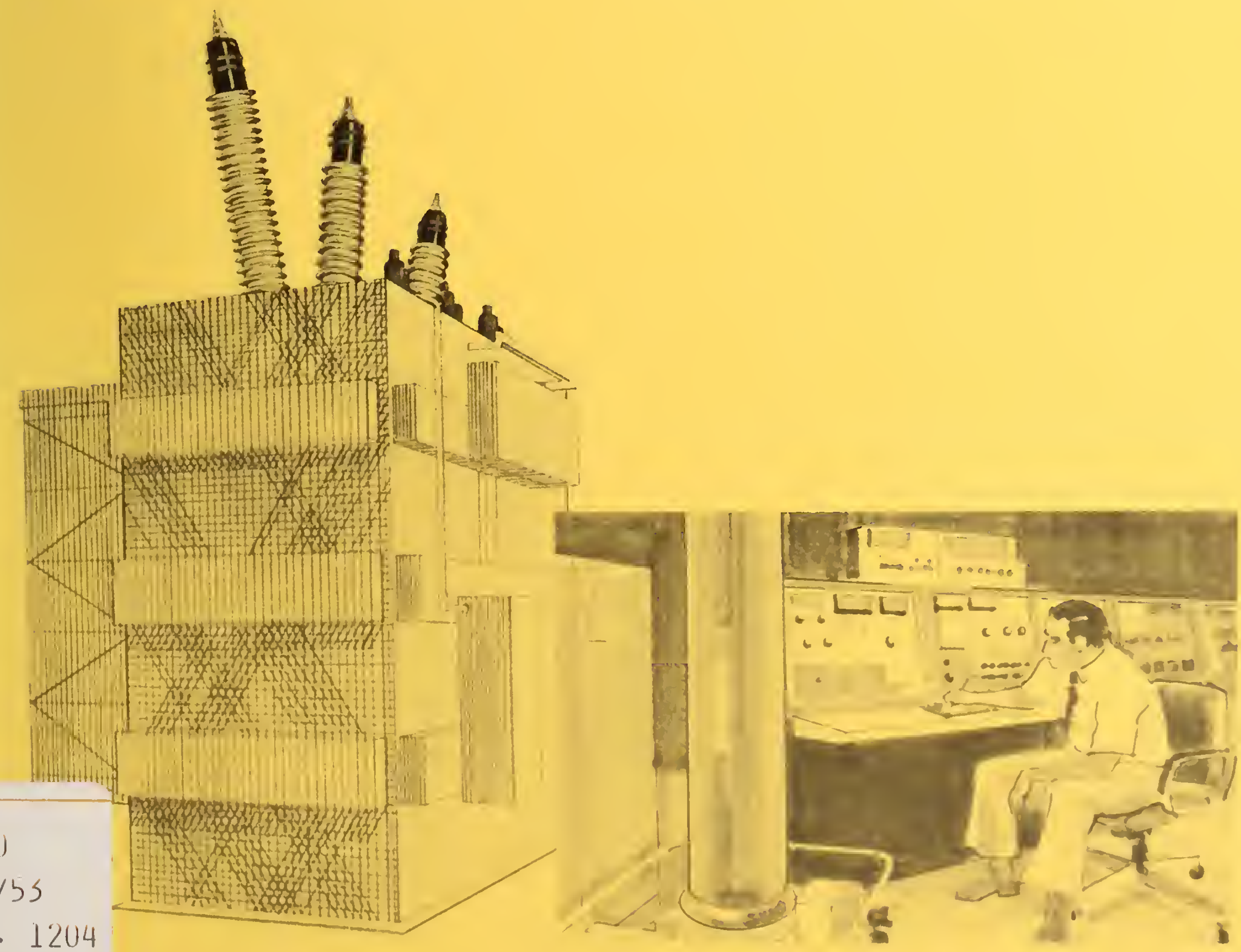
NBS Technical Note 1204

Calibration of Test Systems for Measuring Power Losses of Transformers

Oskars Petersons
S.P. Mehta



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[3] Located at Boulder, CO, with some elements at Gaithersburg, MD.

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FOREWORD

This technical note reports on the work conducted by ASEA Electric, Inc., and the National Bureau of Standards under the NBS Industrial Research Associate Agreement. The calibration system was built and experiments were conducted by ASEA Electric, Inc., under the design and development guidance of NBS. Several special calibrations were performed by NBS for this project on a reimbursable basis following the usual NBS practices.

Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identificaion does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment are necessarily the best available for the purpose.

The use of the developed calibration instruments might be associated with hazardous voltages. The calibration instruments must be used in conformance with the applicable safety codes, standards, and practices.

ACKNOWLEDGMENTS

During the development work and preparation of this report, the authors received assistance from numerous colleagues at ASEA Electric, Inc., the National Bureau of Standards, and other organizations. Jeffrey J. Nemec constructed the equipment and conducted the experiments. Arnold G. Perrey and Wilbur C. Sze provided valuable guidance in the design of the standard current transformer and active divider. W. E. Anderson, N. M. Oldham, and T. M. Souders performed special high accuracy calibrations. C. P. DeWitt of Holt Instrument Laboratories kindly provided the design information on special shunts. Betty Meiselman typed the manuscript under tight deadline conditions. Special thanks to Steven P. Moore and Albert C. Swenton for supporting the project and for their guidance related to measurement requirements. The authors gratefully acknowledge the following readers of the manuscript: B. C. Belanger, N. M. Oldham, S. P. Moore, W.J.M. Moore, K. R. Reed, E. So, and J. R. Sorrells.

EXECUTIVE SUMMARY

It is estimated that average annual capitalized cost of losses in transformers in the U.S.A. is around two billion dollars. The economic impact of power transformer losses is at a state where the cost of evaluated losses over the lifetime of a power transformer often rivals the initial price of the transformer.

With increasing cost of electric energy over the past decade, demands for improvement in efficiency of power transformers has been rising. Improvement in efficiency is achieved by reduction in transformer losses.

Power factor during the load loss test is a ratio between the effective resistance (losses) of a transformer and the effective impedance of a transformer. Reduced losses with effective impedance remaining essentially the same means that the power factor during the load loss test gets smaller as losses are reduced.

Accurate measurement of losses in transformers at low power factor poses difficult technical problems. At low power factor a small phase angle error anywhere in the test system (such as in voltage transformers, current transformers, and power transducers) can cause large error in the measurement of real power. For example, a very small 290 microradian phase error at 1% power factor produces a 2.9% error in the measurement of real power.

Although accurate measurement of transformer losses is very critical, requirements for measurement accuracy and traceability of measurements to higher echelon standards is not addressed in any industry standards.

High phase angle accuracy devices have been developed and utilized in various laboratories for accurate measurements at low power factors. However, this technology in general is not uniformly utilized for critical measurements in industrial environment.

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In this report a system is described that was developed to calibrate and verify the accuracy of test equipment utilized for measuring the losses of large power transformers. Several standard instruments were either constructed or acquired from commercial sources. Methodologies were developed for (a) calibrating and aligning the test systems, (b) for calibrating and maintaining the standards themselves and (c) for ensuring the traceability of measurements.

Specifically this report describes:

1) Development and construction of a two-stage transformer and ancillary devices having a phase angle uncertainty of ±13 μrad.

2) Development and construction of an active voltage divider and standard capacitance networks having a phase angle uncertainty of ±14 μrad.

3) Development of an active phase shifter for the calibration of power transducers having a phase angle uncertainty of ±20 μrad.

4) Methodology for alignment of voltage, current, and power transducers in the test system for loss measurement.

5) Methodology for determining measurement system error vs. power factor.

6) Results of system based verification where simultaneous measurement of losses with a calibration system and test systems are carried out.

7) Requirements for calibration and maintenance of standards and alignment of the test system to maintain traceability to the higher echelon standards.

It is hoped that this report will contribute to the development of industry standards that include accuracy and traceability requirements for test systems utilized for the measurement of transformer losses. Only in this way can there be fair and uniform comparisons of transformer losses by the purchasers of power transformers.

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FOR MEASURING POWER LOSSES OF TRANSFORMERS

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ABSTRACT

A calibration system for accuracy verification and alignment of test systems for measuring transformer losses is described. Methodologies are presented for assessing measurement uncertainties and for evaluating overall accuracy of test systems. Procedures are suggested for continuing maintenance and calibration of standard instruments and test systems to ensure traceable measurements.

Keywords: calibration; loss measurement; low power factor; power transformers; traceability

1. INTRODUCTION

This report describes a system that was developed to calibrate and verify the accuracy of test equipment utilized for measuring the losses of large power transformers. Several standard instruments were either constructed or acquired from commercial sources. Various methodologies were developed for calibrating and aligning the test systems, for calibrating and maintaining the standards themselves, and for ensuring the traceability of measurements to higher echelon standards. Because of the low power factor, measurement of load or conductor loss is particularly difficult and subject to significant uncertainties. Hence, the calibration system is particularly designed to reduce uncertainties that relate to measurements of load or conductor losses, but the system can be utilized equally well to verify the test system for measurement of no-load or core losses.

At low power factors a small phase error anywhere in the test system such as in the current and voltage transformers, and in the power transducer, can cause a large error in the measurement of the real power. This error increases as the power factor decreases. For example, when measuring the losses of a transformer having a power factor of 0.01, an error in the phase angle of one minute (0.29 milliradian) causes an error of 2.9% in the measured power. If an error of 0.29 milliradian is probable in <u>each</u> critical component, -- voltage, current, and power transducer, -- the combined root-sum-of-squares error in the power measurement becomes 5.0%. While an uncertainty in the phase angle of 0.29 milliradian is not at all difficult to achieve in laboratory conditions, it may not be so in industrial testing areas. For example, the standard for instrument transformers, ANSI C57.13, specifies the lowest calibration uncertainty of ±3 minutes for both the voltage and current transformers that are used in revenue metering applications. For applications discussed here, ten to fifty times smaller phase angle errors are required for each of the critical components in the test system, in order to maintain the overall measurement uncertainty for real power in the one percent range.

The phase angle error of various laboratory devices — such as special voltage and current transformers, inductive dividers, gas-dielectric capacitors, and voltage dividers based on such capacitors — is well within the ±50 µrad level. However, this measurement and instrumentation technology is not universally available to the potential users in industry. Also the calibration infrastructure whereby a test system could be readily verified and made traceable* [1] to higher echelon physical standards and whereby tests could be repeated and the results compared among various suppliers and users is not well established.

While it is acknowledged that accurate measurements of transformer losses is a difficult technical problem, there are strong economic and technical motivations for improving the measurement accuracy and for establishing a uniform basis for assessing the measurement accuracy. This relates directly to the increasing cost of electric energy over the past decade which brought about a growing demand for improvements in power transformer efficiency. In order to minimize the estimated 10% energy loss between the points of generation and the end use of electricity [2], power transformer specifications almost invariably include evaluation of transformer losses in determination of the total owning cost of the transformer.

Economic impact of power transformer losses is at a state where over 90% of inquiries include loss evaluation and the cost of evaluated losses often rivals the initial price of transformers. Loss evaluations as high as $10,000/kW for no-load loss and $5,000/kW for load loss are not uncommon with the average being about $4000/kW for no-load loss and about $2000/kW for load loss. It is estimated that the average annual equivalent capitalized cost of losses in transformers in the U.S.A. is around two billion dollars. In this climate, accurate measurement of transformer losses has received considerable attention in recent years.

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*The term "traceability" is frequently used with measurements and calibrations. However, a universally accepted definition for this term has evaded formulation [1]. The definition 3 and parts of definition 2 of reference 1 summarize well the key elements of this term. Quoting from this reference:

"Traceability means the ability to relate individual measurement results to national standards or nationally accepted measurement systems through an unbroken chain of comparisons."

"Measurements have traceability to the designated standards if...scientifically rigorous evidence is produced...to show that the measurement process is producing measurement results (data) for which the total measurement uncertainty relative to national or other designated standards is quantified."

From the manufacturer's viewpoint, improvements in loss measurement accuracies are highly desirable because any upgrading in manufacturing processes, in materials, and in designs intended for reduction in losses would be difficult to evaluate without accurate measurements of transformer losses. From the user's viewpoint, the valididy of the whole selection process, including fair comparison of losses becomes questionable without accurate measurement of transformer losses.

Standardization: It is very important that the issue of loss measurement accuracy be addressed in the industry standards so that uniform comparisons and evaluations of transformer losses can be realized. At present, industry standards dealing with transformers do not address the issue of transformer loss test accuracy. However, work is under way to review the critical factors that have impact on loss measurement accuracy. Appropriate correction factors and their proper use are being developed in a working group of the Transformer Committee of the Institute of Electrical and Electronics Engineers.

In addition to accurate loss measurements, it is equally important that the accuracy of the test system be independently verifiable and traceable to nationally accepted standards. The National Bureau of Standards (NBS) calibrates certain high-accuracy physical standards such as instrument transformers, high-voltage capacitors, and power transducers, all of which could be applied to the calibration of the test system for loss measurements. NBS also receives inquiries from the industry about viable calibration alternatives for such test systems. Occasionally requests have been received to perform spot checks of actual on-site test systems. The NBS interaction with the industry in this area has been hampered by an inadequate measurement infrastructure: unavailability of stable physical standards that could be calibrated at NBS and then used to verify the test system; instabilities in the physical standards making it difficult to transfer the calibration from NBS to the user and to maintain it at the user's facility for any length of time; and nonuniformity in the input and output quantities of the standard instruments thus making it difficult to calibrate them at NBS without resorting to special and very expensive calibration setups.

Calibration of the actual test system by NBS on-site has some merits but also serious disadvantages. Admittedly, such NBS activity could be considered a welcome addition to the in-house calibration procedures since it would provide additional assurance of the validity of the procedures used. However, without proper in-house procedures, NBS on-site calibration might be of limited value. Time constraints and expense would dictate that only a few test points be covered; there would be little time for uncovering the causes of erroneous measurements; and there would be no assurance of how well the test system will behave in the future.

In response to requests for advice on calibration procedures, NBS has recommended that industrial organizations become self-sufficient in calibration capabilities insofar as it is economically feasible so that only a minimal number of standard instruments would have to be sent to outside calibration organizations such as NBS. ASEA Electric was interested in establishing such a calibration system and sought NBS advice. Arrangements were made within the NBS' Industrial Research Associate Program whereby NBS will provide to ASEA Electric design and development guidance for the establishment of physical calibration standards and procedures. ASEA Electric will construct and purchase the necessary instruments and will conduct the experiments. Results of the investigation will be published in the open literature.

One of the goals was to establish a calibration system that is as much as possible self-contained, requiring only relatively few and infrequent calibrations from outside. A second goal was to have the calibration system traceable. Thirdly, for the two principal components in the calibration system — the standard current transformer and the voltage divider — the initial maximum uncertainty goal was ± 30 μrad each, and ± 50 μrad for the third component — the standard power transducer — leading to the combined rss uncertainty of ± 66 μrad. Actual results were better than this goal, with an uncertainty of about ± 33 μrad. After alignment of the test systems against the calibration standards, it was found that the factors that limit the accuracy are predominantly the residual nonlinearities in the transducers and the associated electronics in the test systems.

2. TEST SYSTEMS FOR TRANSFORMER LOSSES

2.1 General Description

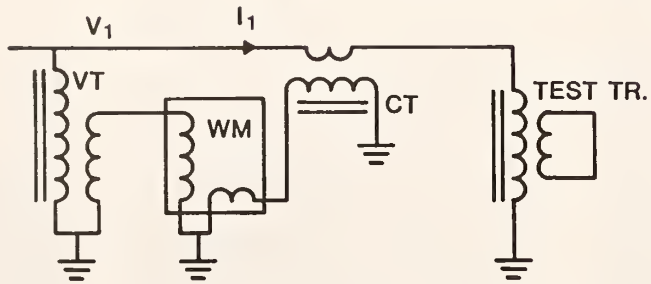
Test systems for measuring transformer and shunt reactor losses are supplied by several manufacturers. Such systems may differ from each other in fine detail, however, their general layouts have considerable commonality.

All test systems contain precision devices to scale (step down) the test voltage for the measurement purpose. The voltage scaling devices can be either precision voltage (potential) transformers or gas-dielectric capacitors. Current scaling is accomplished with precision current transformers, which also isolate the measuring circuit from high voltage. To accommodate three phase devices, current is usually measured in the high voltage circuit. The actual power measurement is performed with a wattmeter (power transducer) designed to have low phase angle uncertainty, or with an impedance bridge.

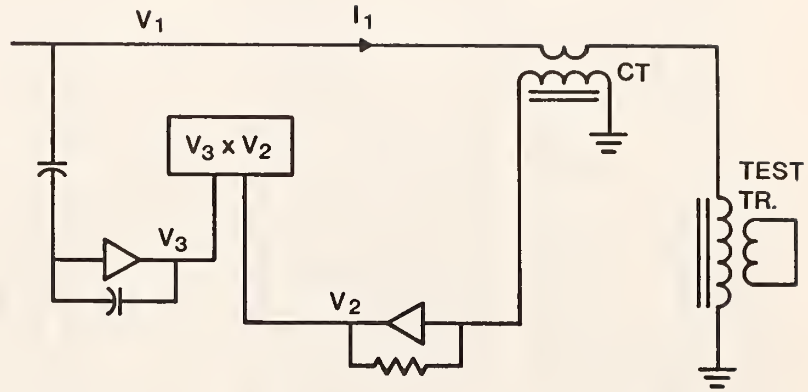
Conceptually, the test systems for transformer loss measurement are illustrated by the four circuit diagrams in Fig. 1. In the circuit of Fig. 1(a), the test voltage and current are reduced with precision instrument transformers and the power is measured with a low-power-factor wattmeter. In Fig. 1(b), an active voltage divider is employed to scale down the voltage. The reduction of current is achieved with a current transformer to which an amplifier is connected in order to obtain the signal with the required amplitude; the outputs of the two amplifiers are voltages, hence a voltage multiplier-type of transducer is used. In Fig. 1(c), a bridge technique is illustrated. This particular bridge, employing a high voltage capacitor and a current transformer, has some similarities to the classical Schering and Maxwell bridges [3]. In Fig. 1(d), another bridge technique employing a high voltage capacitor, a current transformer, and a transformer-ratio-arm bridge is shown [4,5,6].

For single-phase measurements the current transformer can be connected in the ground lead as in Fig. 1(d); in three-phase measurements, the current transformers are in the high voltage lead as in Figs. (a), (b), and (c). Special high accuracy current transformers such as zero-flux transformers, two-stage transformers, or amplifier-aided transformers are necessary. Similarly, high accuracy, especially for the phase angle, is required in the voltage transformers, the high voltage dividers, or the capacitors. The wattmeter or watt transducer should be suitable for measurements at low power factor and should have small phase angle uncertainty. Methods employing wattmeters or power transducers are most suitable for power factors in the approximate range of one percent or higher. For power factors substantially below one percent as encountered in shunt reactors, bridge techniques may have to be considered.

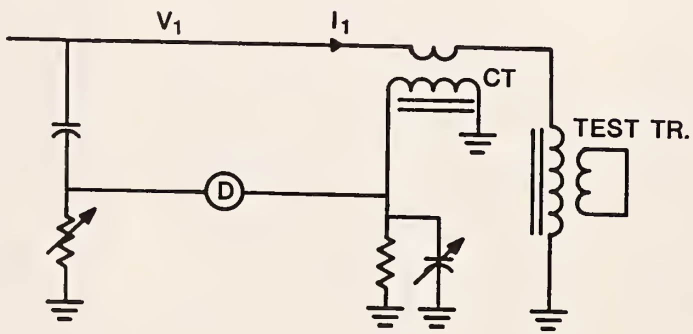
ASEA Electric utilizes two independent test systems for measuring transformer losses. Both systems are of the general type shown in Fig. 1(b) enabling measurement of losses on a three-phase basis using the three-wattmeter method. The first of these two systems was placed in service in 1971, the second in 1980. Following is a brief discussion of the salient features of these two systems.



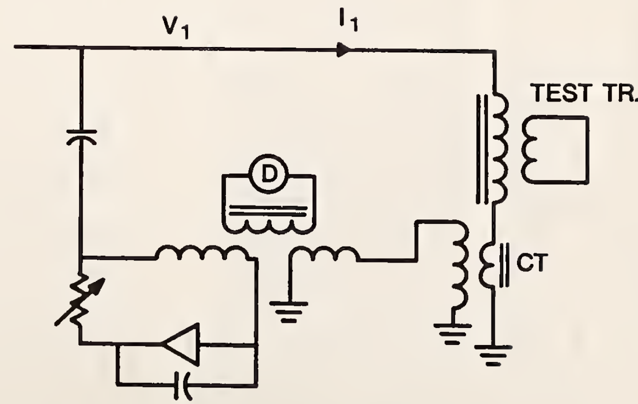
(a) Based on voltage and current transformers and a wattmeter



(b) Based on a current transformer, a high voltage divider and a power transducer



(c) Based on an RC-type impedance bridge



(d) Based on a transformer-ratio-arm bridge

Figure 1. Conceptual Circuits for Measuring Transformer Losses

2.2 Test System 1

A simplified schematic representation of test system 1 is shown in Fig. 2. The system is divided into three principal subsystems — the first for scaling and measuring the current, the second for scaling and measuring the voltage, and the third for measuring the power.

The current subsystem (or the current channel) includes scaling of the primary current by means of a zero-flux current transformer. Three such transformers, one for each phase, are inserted in the high voltage line. The transformers are gas insulated for 100 kV. Secondary currents from the working and control windings are passed through the main and compensating burdens located in the console. Separate sets of burdens are provided for each of the four ranges of the primary current — 10A, 100A, 1000A, and 10,000A. Compensating burdens are adjusted during the calibration and alignment process of the test system. The voltage at the main burden is supplied through a precision buffer amplifier to the rms current transducer, peak current transducer, and power (watts) transducer. The design of the amplifiers permits small adjustments in the in-phase and quadrature components of gain in order to facilitate the alignment of the system.

The voltage subsystem (or the voltage channel) utilizes a gas-dielectric high voltage capacitor in an operational integrator configuration as shown to the right in Fig. 2. The three ranges for the primary voltage — 1 kV, 10 kV, and 100 kV — with a corresponding secondary voltage of 10 V, are achieved by changing the gain in the ranging amplifier that follows the integrator. Small adjustments can be made in the gain of the ranging amplifier. The output voltage of the ranging amplifier is supplied to the rms, average and peak voltage transducers and to the power transducer.

The power measuring subsystem consists of a power transducer (time division multiplier) and scaling amplifiers, both at the input and output of the transducer, to enable operating the transducer near its full scale. The gains of the output amplifiers are reciprocals of the gains of the input amplifiers.

The principal accuracy-related specifications as originally supplied by the manufacturer of the test system are the following:

a. voltage (rms, average, peak): ±0.5% of reading; from 10% of full scale to full scale; three ranges — 1kV, 10kV, 100kV

b. current (rms, peak): ±0.5% of reading; from 10% of full scale to full scale; four ranges — 10A, 100A, 1000A, 10,000A

c. power: ±5.0% of reading at power factor of 0.01;
±0.5% of reading at power factor of 0.1;
0.1 kW to 10 MW in 72 ranges.

In order to improve the accuracy of power measurements, especially at low power factors, several of the amplifiers and the power transducer were rebuilt to take advantage of more stable components and circuit configurations. However, the overall functional layout of the test system was left unchanged. The accuracy figures discussed in section 8 are those for the rebuilt system after it was calibrated and aligned.

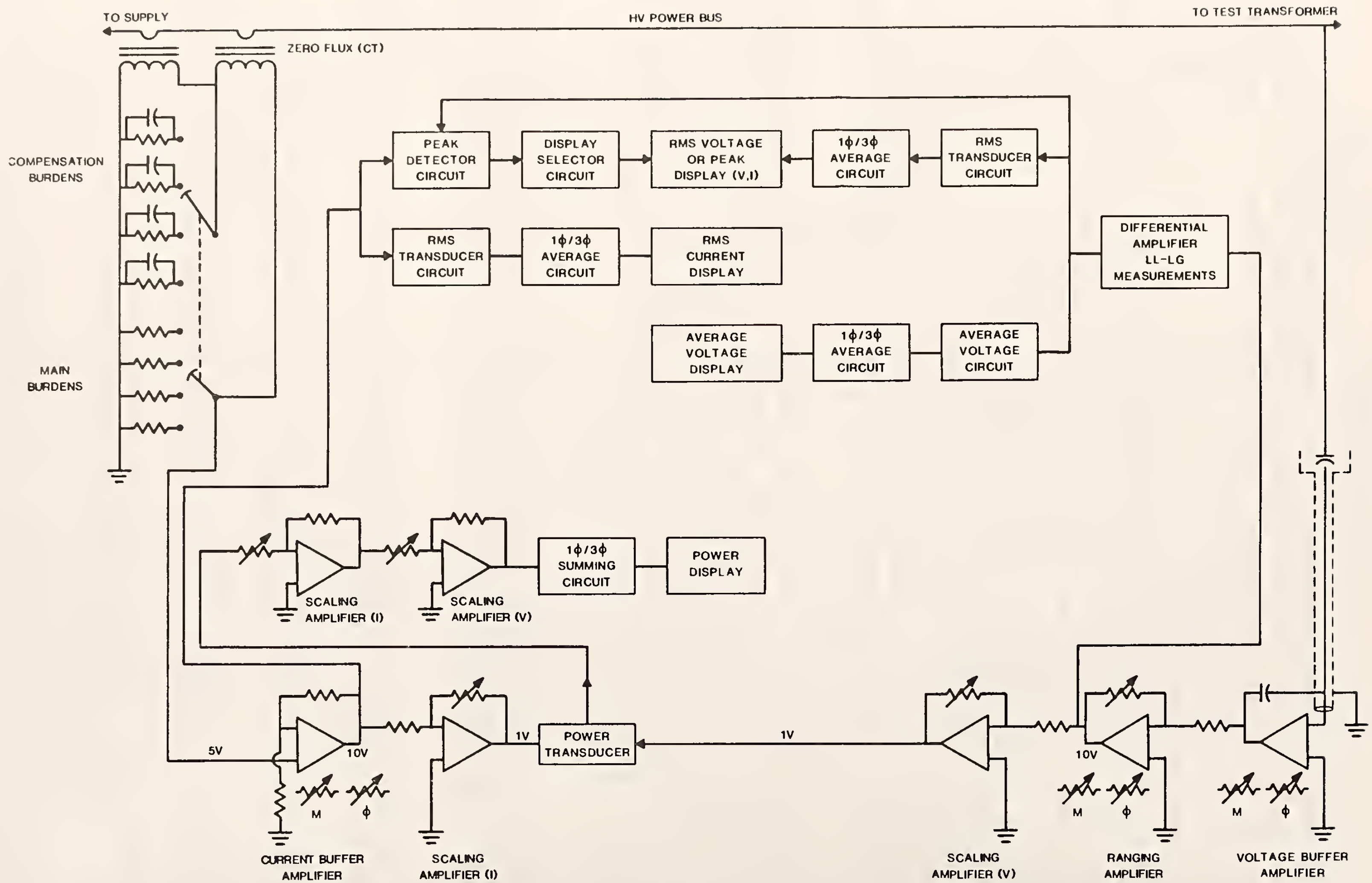


Figure 2. Test System 1 - Block diagram showing principal components

2.3 Test System 2

A simplified block diagram of this system after modifications is shown in Fig. 3. The basic concepts are similar to those of the test system 1 with the following exceptions: current scaling is accomplished with a two-stage current transformer; the maximum operating voltage is 230 kV, the maximum current is 1000A; as originally built, this system did not include scaling amplifiers in conjunction with the power transducer.

The principal accuracy-related specifications of the test system before alignment were as follows:

a. voltage (rms, average, peak): ±0.3% of reading; at 10% of full scale and above; four ranges — 1 kV, 10 kV, 100 kV, and 230 kV

b. current (rms, peak): ±0.3% of reading; at 10% of full scale and above; four ranges — 1A, 10A, 100A, 1000A

c. power: ±0.3% of reading at power factor of 1.0;
±0.6% of reading at power factor of 0.1;
±4.0% of reading at power factor of 0.01;
0.1 kW to 100 MW in 48 ranges

Accuracy improvements obtained after the modification, calibration, and alignment are discussed in section 8.

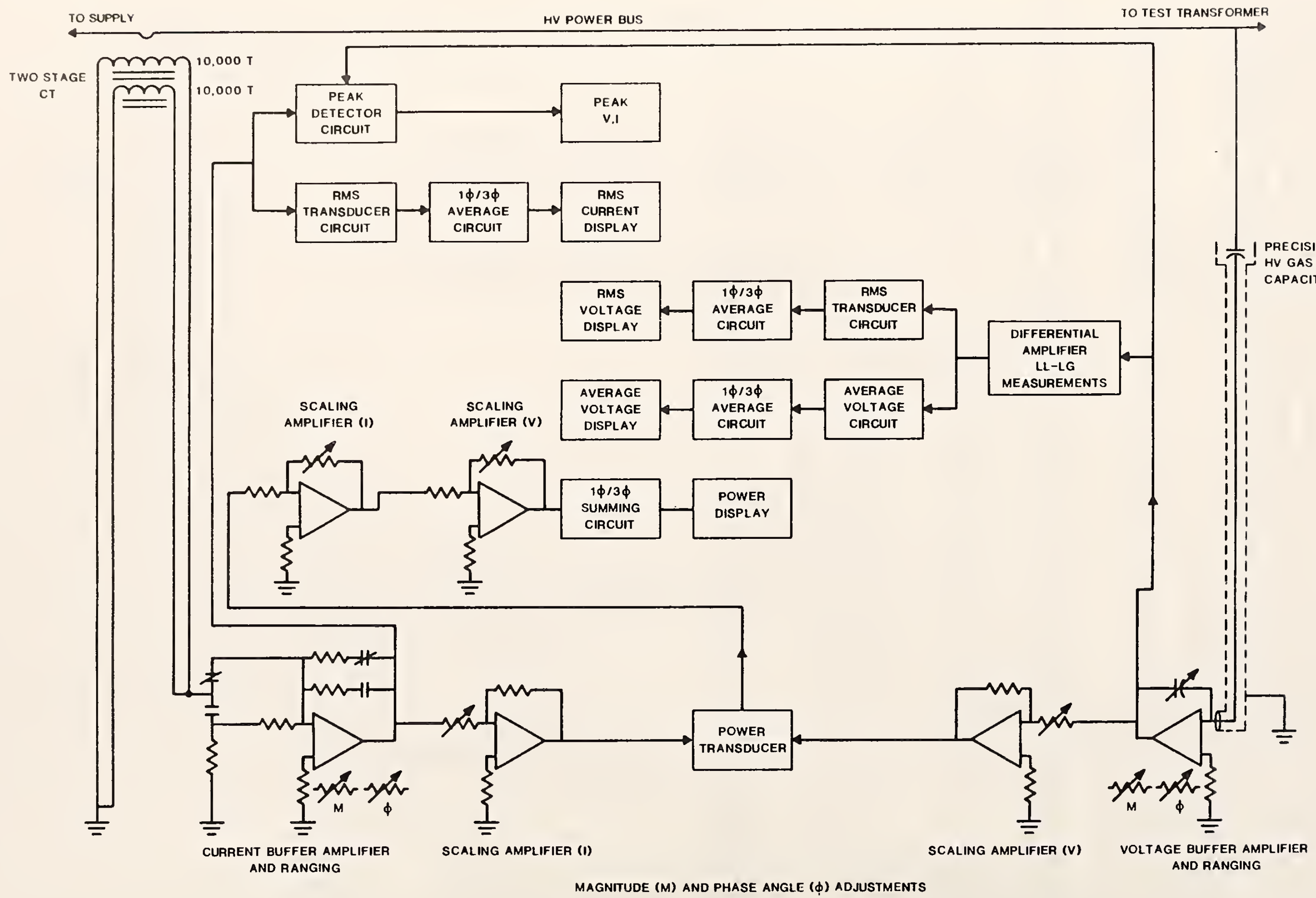


Figure 3. Test System 2 - Block diagram showing principal components

3. CALIBRATION APPROACH

The two test systems for which the calibration system is designed are of the type shown in Fig. 1(b), consisting of amplifier-aided capacitive dividers, special current transformers connected to the amplifiers, and power transducers (voltage multipliers).

It is desirable to verify the accuracy of a test system on a system basis by simultaneously measuring voltage, current and power with the test system and with the calibration (standard) system. Such a comparison can be conveniently performed on a single-phase basis. A system-based verification is essential as the final check to ensure that there are no adverse interactions among the components in the test system and that various electromagnetic interferences do not cause excessive errors. A system-based verification by itself is insufficient when large discrepancies are found in the measurements, since the causes of such discrepancies are more difficult to identify. Since such discrepancies could be caused by malfunctions in the test system, it would be an undesirable practice to correct the final result without correcting the cause of the discrepancy.

In recent years significant developments in accurate measurements of losses in the power system apparatus at very low power factors have been reported. Most of these developments have as their basis the current-comparator-based bridge techniques [4,6,7,8,9]. These developments are directly applicable for the system-based verification of the test systems utilized for measurement of losses in power system apparatus.

The approach taken in designing the calibration system described in this report was to make it suitable not only for a system-based verification but also for verification of the principal components in the test system — the high voltage divider, the current transformer, and the power transducer. Further considerations for selecting this approach were the architecture of the two test systems at ASEA Electric (it is a commonly used architecture in other test systms); desirability to have a calibration process that is as much as possible self-contained requiring relatively few calibrations from outside; realistically achievable and maintainable accuracy in an industrial test environment; and cost effectiveness of the total approach. The calibration or standard system consists of four basic parts:

1. a two-stage current transformer with precision shunts; for calibration and alignment of the current transformer and its ancillary components in the test system, for supplying signal to current and power measuring instruments;

2. an active voltage divider based on a compressed-gas high voltage capacitor; for calibration and alignment of the voltage (potential) transformer or the high voltage capacitor and its ancillary components in the test system, for supplying signal to voltage and power-measuring instruments;

3. a standard power transducer (voltage multiplier); for calibration of transducers in the test system; and

4. an active phase shifter also to calibrate the power transducers at various power factors, e.g., 0.00, 0.01, 0.02, 0.05, and 0.10.

With such a calibration system, the test systems in Fig. 1(a) and Fig. 1(b) and their principal components can be readily calibrated. With a few additional components, the calibration system can also be adapted for the verification of the impedance bridges as shown in Fig. 1(c) and Fig. 1(b). Sections 4 to 6 describe the calibration procedures in general, while section 7 presents the procedures and calibration results for the two specific test systems at ASEA Electric.

The components of the calibration (or standard) system can be configured in a self-contained power-measuring system, thereby enabling verification of the test equipment on a system basis as shown in Fig. 4.

The calibration system itself is readily verifiable and calibratable against higher echelon standards. Most of the calibrations can be performed in-house with minimal help from outside calibration laboratories, including NBS. Finally, the entire measurement process, including the loss measurement of the transformer, is traceable.

To facilitate the verification of the calibration instruments in-house, several other instruments were acquired: an inductive divider, a standard 1000-pF low voltage capacitor, a high quality ac voltmeter, and a null detector. The two-stage current transformer was designed to serve in several other calibration roles besides the principal one of calibrating the current channel in the test system.

The total instrumentation package for calibration of test systems is relatively small, consisting of 13 instruments and impedance standards. All are shown in Fig. 5.

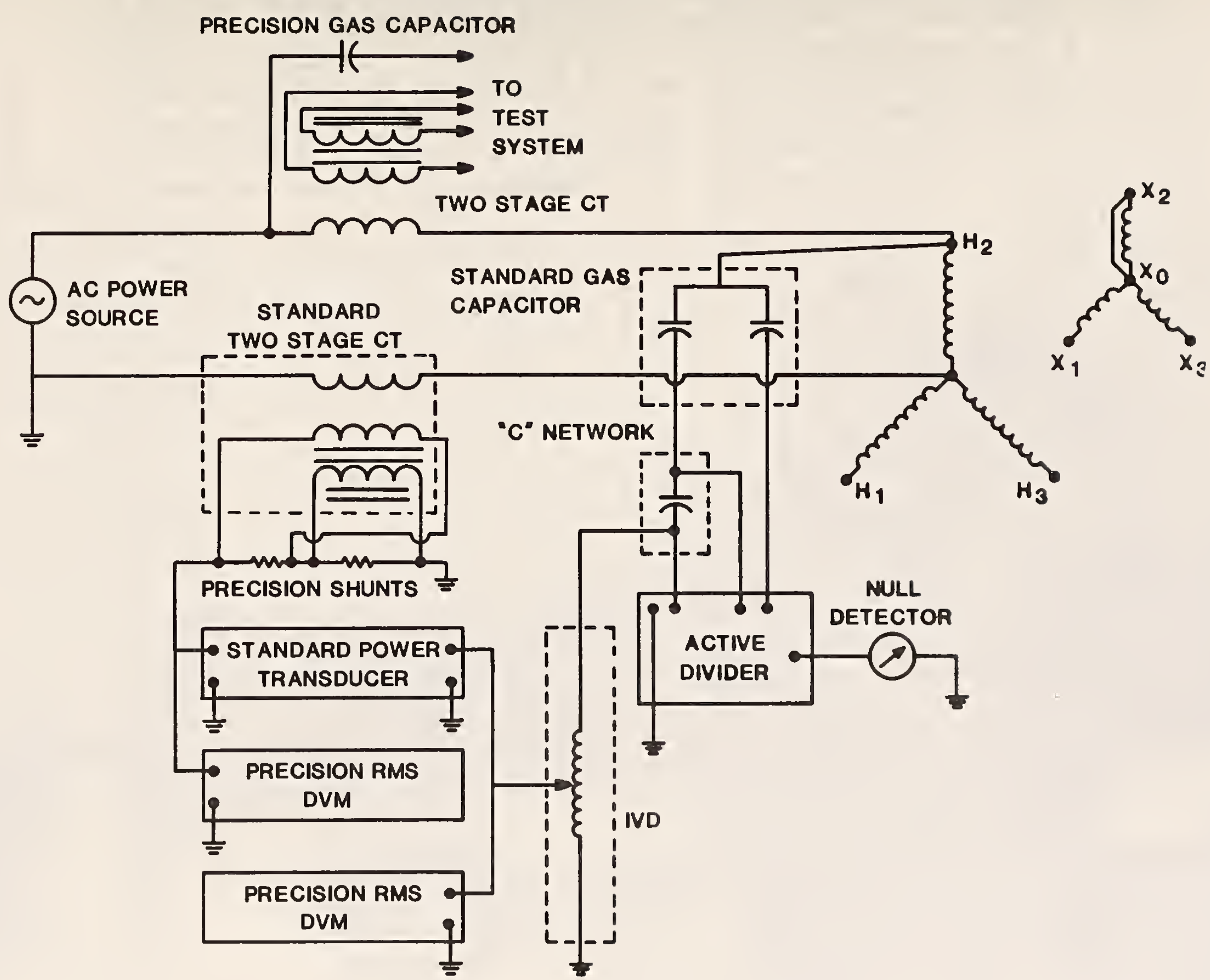


Figure 4. System Based Verification

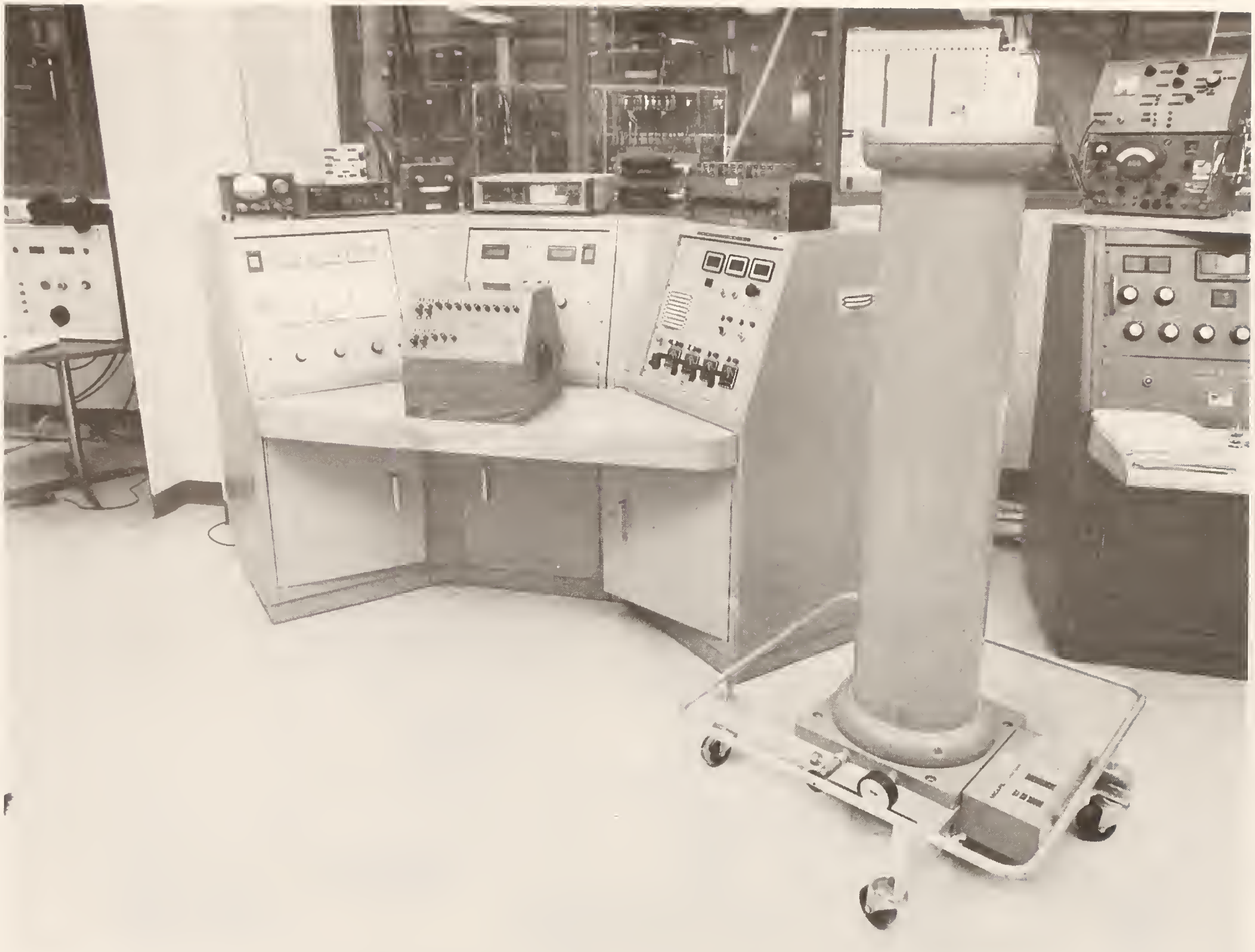


Figure 5. Instrumentation for Calibration of Test Systems - Test system 2 (console), two-stage current transformer (on desk of console), high voltage standard capacitor (at right), null detector (on console at left), standard power transducer, electronics for active voltage divider (on top of power transducer), 1000-pF standard capacitor, precision DVM, two 2-ohm shunts, inductive voltage divider, three precision capacitive networks (on top of inductive divider)

4. CALIBRATION OF CURRENT CHANNEL

4.1 General Approach

The current transformers in both test systems have a single ratio, and thus operate over a wide dynamic range. For example, the secondary currents range from 10 mA to 10 A for the primary currents of 10 A to 10,000 A in one of them. The nominal output voltages of the amplifiers are maintained within the optimum range of 2 V to 10 V by changing the impedances in the networks associated with the feedback amplifiers. The errors of the amplifier circuit enter directly into the measurement error.

In designing the calibration equipment and procedures, the objective was to keep them simple. Consequently, the physical standards for calibration of the current channels in the test system consist of a two-stage current transformer and a precision two-ohm resistor (shunt). The current transformer has three principal ratios of 1000 A/1 A, 100 A/1 A, and 10 A/1 A, obtained by changing the number of turns in the primary winding. By using a multi-ratio current transformer, the dynamic range for the secondary current can be maintained between 0.1 A and 1.0 A.

The current channels in both test systems are of the general type shown in Fig. 1(b). The outputs of the current transformers are converted to voltages by means of transimpedance circuits containing precision resistors and feedback amplifiers. The transimpedances in the test systems are calibrated and adjusted against the standard current transformer and the precision shunt by utilizing a circuit as shown in Fig. 6. For simplicity, the current transformer in the test system at the left is shown as a simple two-winding transformer. The standard two-stage current transformer is at the right. Besides the precision resistor R, another resistor R_1 having the same nominal value as R has to be employed, but R_1 need not be a precision component. The two-stage transformer and the resistors form a high-current transimpedance (or shunt), the value of which is R/n, where n is the turns ratio N_2/N_1.

The two transimpedances are compared in a potentiometric circuit. A seven-decade inductive voltage divider is connected to the output of the amplifier in the test system. The ratio (d) of the inductive divider is set to produce the desired transimpedance (R_x/n_x) in the test system when the detector (D) indicates null.

$$(R_x/n_x)d = R/n, \qquad (1)$$

$$d = (R/R_x)(n_x/n), \qquad (2)$$

where n_x is the turns ratio of the current transformer in the test system, and R_x is the resistance associated with the amplifier circuit in the test system.

In the actual alignment operation of (R_x/n_x), the effective resistance and its phase angle are adjusted until the balance condition is achieved. The phase angle errors of the standard resistor, the two-stage current transformer, and the inductive divider are negligible.

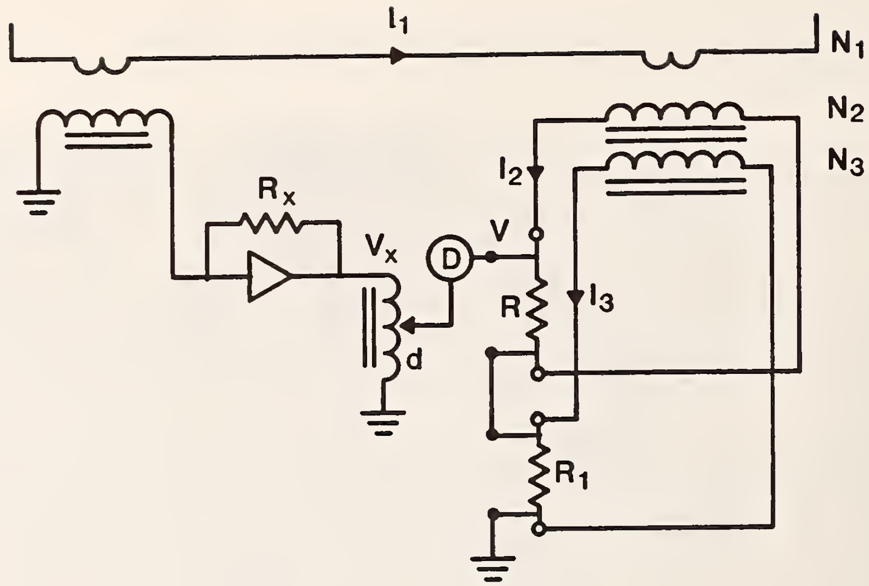


Figure 6. Calibration of current channel, $V_x > V$

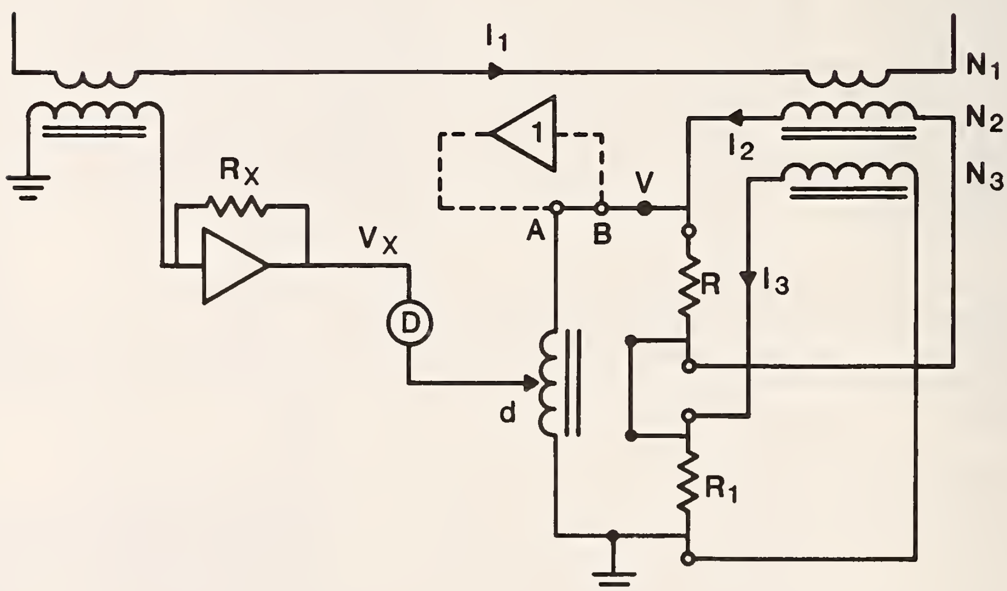


Figure 7. Calibration of current channel, $V > V_x$

If the voltage at the output of the amplifier is smaller than that at the standard current transformer, the inductive divider must be connected to the terminals of the standard current transformer as in Fig. 7. This configuration introduces an error, predominantly in the phase angle, since the effective resistance R is modified by the input impedance of the inductive divider in parallel with R. A correction must be made for this error. Alternatively, a buffer amplifier presenting an infinite input impedance to the current transformer and zero output impedance to the detector can be inserted between points A and B in Fig. 7. A simple buffer amplifier with bipolar output and unity gain is shown in Fig. 8(a). The buffer amplifier can be readily aligned for exact unity gain by using the null detector in the two connections, as in Fig. 8(a), and injecting a small current from the circuit in Fig. 8(b).

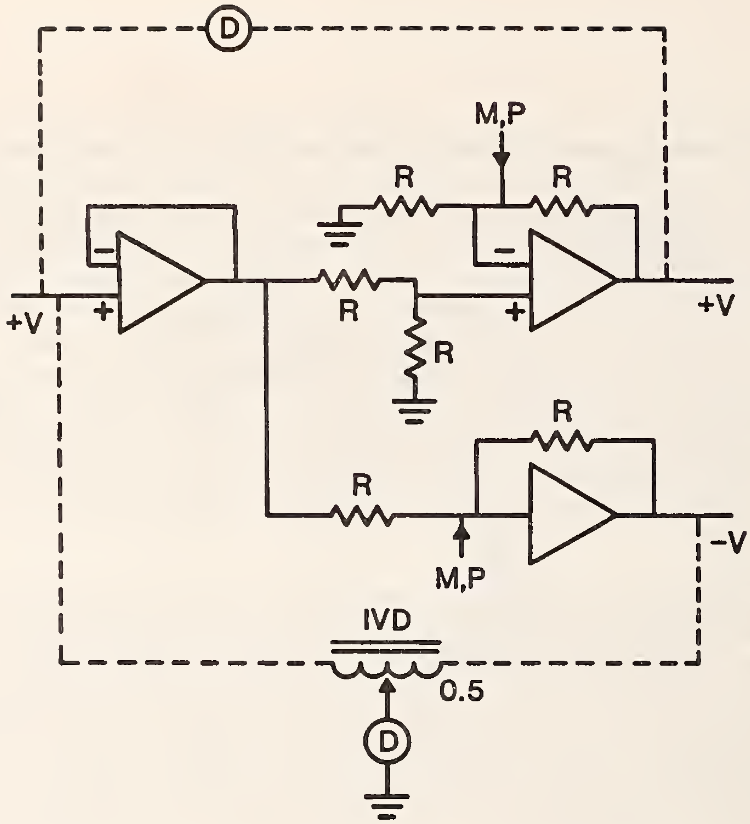
Since relatively small phase angle errors could lead to large errors in the test system when measuring power, precautions must be exercised so that the calibration process itself does not introduce significant errors. The errors in the calibration circuits most frequently arise from grounding problems and from pick up of extraneous 60-Hz signals by the leads and the equipment. Typically, the calibration is performed with 1 to 2 volts on R. An extraneous signal of 100 to 200 microvolts could result in a phase angle error of 100 to 200 microradians. It is prudent to observe the following precautions:

1. Avoid multiple grounds and thus possible significant voltages between these grounds. Test the voltage between the grounds if multiple grounding exists. For example, connect the null detector across the two grounds in the circuit of Fig. 6 when the circuit is energized.

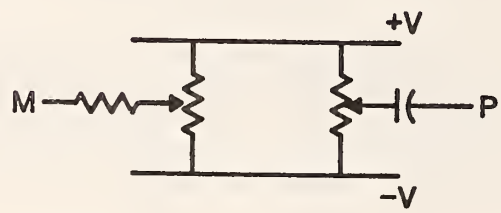
2. Keep the leads short and wiring orderly; avoid high impedances in critical wiring due to poor connections.

3. Keep the calibrating equipment and wiring away from high electrostatic and magnetic fields. Keep the loops in the wiring small so as to minimize the pickup from magnetic fields. Where applicable, use shielded conductors, e.g., from the standard current transformer and the resistors to the detector.

4. The instruments used as null detectors are frequently sources of pick up. Since the calibrations are done at the power line frequency, battery-energized instruments are preferable. Both inputs of the detector in Figs. 6 and 7 are at a potential above ground; hence, a detector with a differential input can be used. Check that the common mode rejection is adequate by connecting both inputs to the same point, V or V_x, when the bridge is energized. Detectors with single-ended inputs, with one of the inputs being the chasis, will generally function properly in this application since the impedances on both sides of the detector are low, and the chasis-to-ground capacitance will cause no problems. Check the interference caused by external sources by observing the indication of the detector without the circuit being energized.



(a) Schematic circuit diagram



(b) Magnitude and phase angle adjustments; two circuits are required

Figure 8. Bipolar Buffer Amplifier

5. Finally, it should be noted that the standard current transformer is designed only for operation with both windings at or near the ground potential. Since the current transformer in the test system is normally inserted in the high voltage lead, it must be ensured that the same primary current passes through both current transformers.

4.2 Two-Stage Current Transformer -- Theory

A two-stage current transformer is the principal component employed for the calibration of the current channel in the test system. Such a transformer was first described more than sixty years ago; in the more recent past it has been of considerable interest to standards laboratories [10,11]. Its principles are briefly reviewed here by employing equivalent circuits.

For the two-winding transformer of Fig. 9(a), a conventional equivalent circuit is shown in Fig. 9(b). It consists of an ideal transformer followed by a T-network of impedances that are expressed with respect to the secondary winding: Z_m is the magnetizing impedance, and Z_1 and Z_2 are the equivalent primary and secondary leakage impedances, respectively. For power frequency instrument transformers of the type described here, Z_1 and Z_2 are predominantly the winding resistances, and Z_m is predominantly the open-circuit inductance combined with the equivalent conductance resulting from the core losses.

The actual no-load voltage/current ratio of the transformer can be readily calculated from the equivalent circuit.

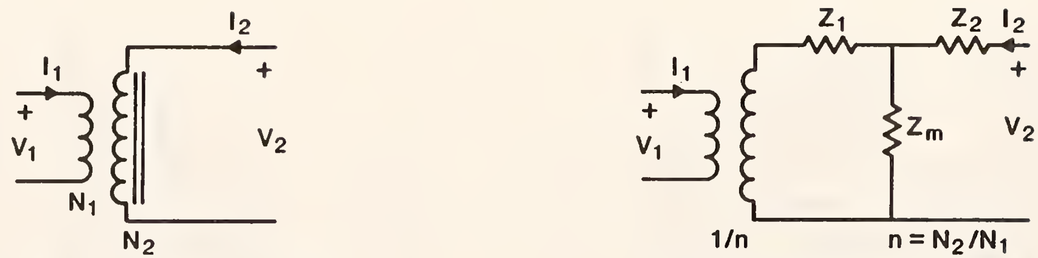
$$(V_1/V_2)_{I_1=0} = -(I_2/I_1)_{V_2=0} = (1/n)/(1+Z_2/Z_m). \qquad (3)$$

Since Z_2/Z_m is small, typically <0.001, the equation (3) simplifies to

$$(V_1/V_2)_{I_1=0} = -(I_2/I_1)_{V_2=0} = (1/n)(1 - Z_2/Z_m). \qquad (4)$$

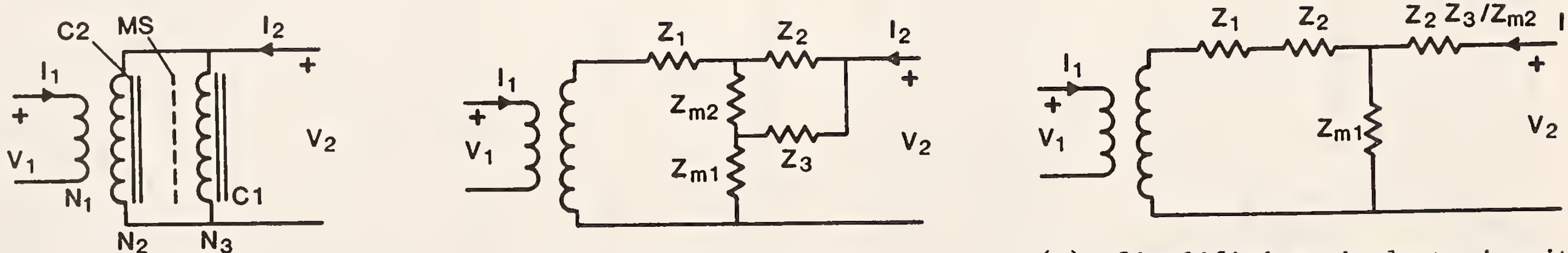
Equation (4) suggests a reciprocal device for which the forward short-circuit current ratio is equal to the reverse open-circuit voltage ratio. Since Z_m is nonlinear, the reciprocity is not valid if very low ratio uncertainties, of the order of ± 0.0001, are desired. For a current transformer that is operated with a burden, the impedance of the burden must be added to Z_2 in order to calculate the current ratio. Z_1 does not affect the current ratio, but influences the voltage ratio if the voltage transformer has a burden.

A two-stage transformer is obtained by adding another core and another winding to a simple transformer. The actual construction is illustrated in Fig. 10(a). A compensation winding, N_3, having the same number of turns as N_2, links only the toroidal core, C1, at its right. For best results, this core and the compensation winding are enclosed in a magnetic shield (MS) to reduce the leakage flux that otherwise would not be confined in the toroidal structure. Another toroidal core, C2, is added and the primary and secondary windings, N_1 and N_2, are wound on the combination of the two toroids.



(a) Circuit diagram (b) Equivalent circuit

Figure 9. Two-Winding Transformer



(a) Circuit diagram (b) Equivalent circuit (c) Simplified equivalent circuit

Figure 10. Two-Stage Transformer

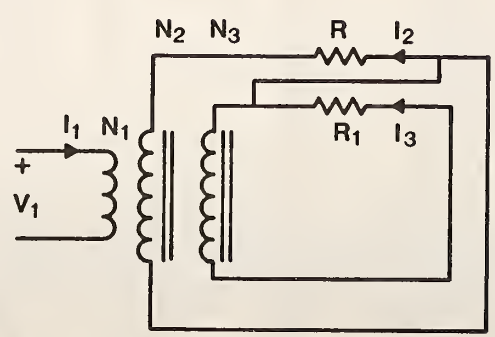


Figure 11. Two-Stage Transformer with Separate Burdens

If the magnetic shielding is perfect and N_3 is magnetically coupled to N_1 and N_2 exactly in proportion to the number of turns, the equivalent circuit of Fig. 10(b) is a valid representation of the device of Fig. 10(a). Z_{m1} is the magnetizing impedance of the core C1, Z_{m2} of C2, and Z_3 is the leakage impedance of N_3. After performing a "π-T" transformation and neglecting insignificant terms, the equivalent circuit of Fig. 10(c) is obtained. In this conventional T-network, the secondary leakage impedance Z_2 is effectively transfered to the primary side where it does not affect the accuracy of an unloaded transformer. The residual secondary leakage impedance, Z_2Z_3/Z_{m2}, is reduced, typically, by a factor of 1000 to 10,000 from the original value and frequently, as in the transformer built in this investigation, can be neglected.

The expression for no-load voltage/current ratios, analogous to eq. (4), is given by

$$(V_1/V_2)_{I_1=0} = -(I_2/I_1)_{V_2=0} = (1/n)[1-(Z_2Z_3)/Z_{m1}Z_{m2})]. \qquad (5)$$

For the transformer that was constructed, Z_2 = 2 ohms, Z_3 = 5 ohms, $Z_{m1} = Z_{m2}$ = j50,000 ohms, yielding the error term of 4×10^{-9}. While this term will vary with the flux density in the cores, it is completely negligible in the applications for which the transformer was constructed. The actual no-load voltage and current ratios are equal to the turns ratio, and the transformer is reciprocal. The equivalent circuits of Fig. 10 have considered only the errors that are of magnetic origin. Internal capacitances will contribute to additional ratio and phase angle deviations, but these deviations do not exceed one or two parts per million in the transformer that was constructed.

Equation (5) applies only to the no-load condition. The advantages of a two-stage current transformer will be defeated by connecting a common burden to both windings, N_2 and N_3. On the other hand, the advantages will be retained by connecting separate, nominally equal, impedances to the two windings as in Fig. 6. Only one of the burden impedances needs to be known to great accuracy [12].

Consider the circuit with two burden impedances as shown in Fig. 11. The combined output current is given by

$$-(I_2+I_3) = (I_1/n)[1-(Z_2+R)(Z_3+R_1)/Z_{m2}Z_{m1}]. \qquad (6)$$

Even with the added burden resistances the error term remains negligible in equation (6). The current I_2 can be calculated from the considerations of a simple two-winding transformer

$$-I_2 = (I_1/n)[1-(Z_2+R)/Z_{m2}]. \qquad (7)$$

Equation (7) is based on the core at the left and the windings N_1 and N_2 being considered the constituents of a transformer. With respect to the core at the right, the effective primary current is the error component given in equation (7). Hence the current in N_3 becomes

$$-I_3 = (I_1/n)(Z_2+R)/Z_{m2}[1-(Z_3+R_1)/Z_{m1}]. \qquad (8)$$

Neglecting the product of error terms,

$$-I_3 = (I_1/n)(Z_2+R)/Z_{m2}. \tag{9}$$

The above discussion considers the two-stage current transformer as a combination of two current transformers: (a) the principal current transformer and (b) the compensation current transformer. The latter compensates for the error of the principal current transformer.

I_2 and I_3, when passed through the two resistors R and R_1, respectively, produce the required voltage V as in Figs. 6 and 7. Thus,

$$V = -I_2R-I_3R_1. \tag{10}$$

Let

$$R_1 = R(1+\alpha), \tag{11}$$

where α is a small deviation.

Substituting (7), (9), and (11) in (10) and neglecting the products of the error terms yields

$$V = (I_1/n)R,$$
$$V/I_1 = R/n. \tag{12}$$

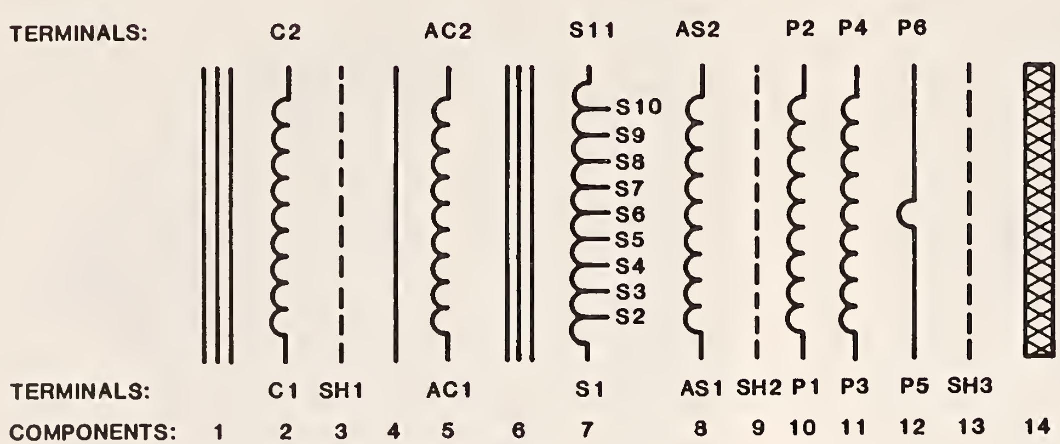
Thus, the effective transimpedance depends only on the value of the precision resistor connected to N_2 and on the turns ratio of the two-stage transformer.

4.3 Two-Stage Current Transformer -- Construction

The components comprising the entire transformer are shown in Fig. 12. The magnetic cores and principal winding are similar to a range extending transformer that was described previously, except only one magnetic shield is used [13]. Starting at the left is the first toroidal core on which a 1000-turn compenstion winding is wound. It is followed by electrostatic and magnetic shields and a 100-turn compensation winding.* Then the second core, identical to the first one, is added. The primary and secondary windings are placed on the combined toroid. Additional windings and taps, beyond those required for the 1000/1, 100/1, and 10/1 ratios, are provided in order to enhance the flexibility of the transformer for performing self-checking operations, and to facilitate the use of the transfomer in impedance bridge circuits. To minimize the winding-to-winding capacitances, electrostatic shields are provided between secondary and primary windings. The assembled unit is mounted in a metal-lined phenolic enclosure with readily accessible terminals as shown in Fig. 13.

*A decision to add this winding was made after the shields were constructed. A preferable place would have been below the two shields. This winding is not critical to the principal operation of the transformer.

STANDARD TWO STAGE CURRENT TRANSFORMER



COMPONENTS

1. SUPERMALLOY CORE #1
2. COMPENSATION WINDING 1000 TURNS
3. ELECTROSTATIC SHIELD
4. MU-METAL SHIELD
5. AUXILIARY COMPENSATION WINDING 100 TURNS
6. SUPERMALLOY CORE #2
7. SECONDARY WINDING 10 X 100 TURNS
8. AUXILIARY SECONDARY WINDING 100 TURNS
9. ELECTROSTATIC SHIELD
10. PRIMARY WINDING – 10 AMPS 100 TURNS
11. PRIMARY WINDING – 100 AMPS 10 TURNS
12. PRIMARY WINDING – 1000 AMPS 1 TURN
13. ELECTROSTATIC SHIELD
14. CASE

Figure 12. Details of Standard Two-Stage Current Transformer

(a) Primary terminals

(b) Secondary terminals

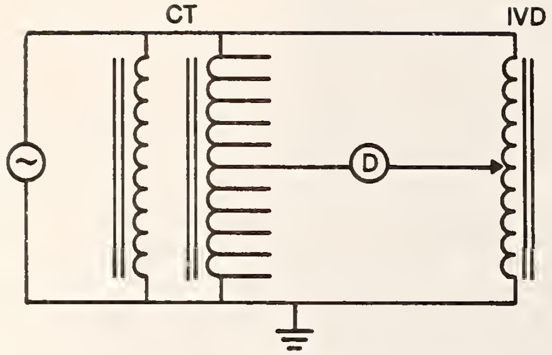
Figure 13. Standard Two-Stage Current Transformer in Enclosure

4.4 Functional Tests of Current Transformer

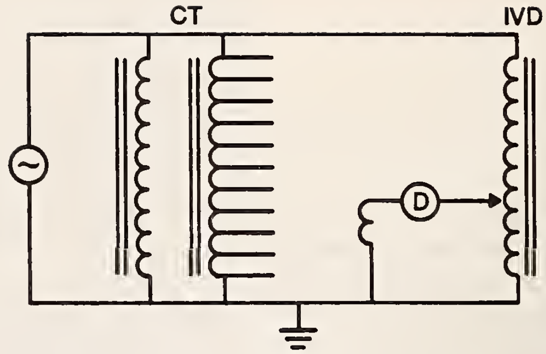
Properly constructed two-stage transformers are rugged and highly stable devices. Most of the failure modes, such as open and short circuits, tend to be catastrophic and are readily apparent. There are no long-term drifts. Subtle failures causing significant ratio errors are possible, e.g., as a result of partial turn-to-turn short circuits in a winding. As a result of the transformer action, the effects of such short circuits are coupled in the other windings of the transformer. Thus the integrity of the transformer can be verified by checking one or two selected ratios without reverting to complete recalibration. Also, if convenient, the checking can be done in the voltage transformer mode.

A circuit for checking the transformer against a standard inductive divider is shown in Fig. 14. An inductive divider can be utilized to check the ratios of all taps of the secondary winding and the ratios of the secondary-to-primary windings. The in-phase component is balanced by adjusting the setting of the inductive divider. The residual phase angle difference is determined from the reading of the null detector. In this case a tuned microvoltmeter used as a null detector yields information on the magnitude of the phase angle only. Hence, a phase-sensitive instrument providing information on the polarity of the unbalanced signal is preferable. Using a seven-decade inductive divider, this method is entirely satisfactory at ratios as low as 0.1 and even 0.01. At a ratio of 0.001, the resolution and the sensitivity may be insufficient.

A self-checking method is outlined in Fig. 15. The 0.1 tap of the 1000-turn winding can be compared to each of the two 100-turn windings. The operation can be repeated by comparing the output between any two adjacent taps with that of a 100-turn winding. An inductive divider can be added for comparing the output of the 10-turn winding to that of the 100-turn. The circuits of Fig. 15(a) and (b) can be operated either in the voltage transformer or the current transformer modes. Again, a phase-sensitive detector is preferable for determining the in-phase and quadrature components of the error. The tests shown in Fig. 15, while not being self-contained calibrations, are excellent means for checking the integrity of the current transformer after a comprehensive calibration has been performed.

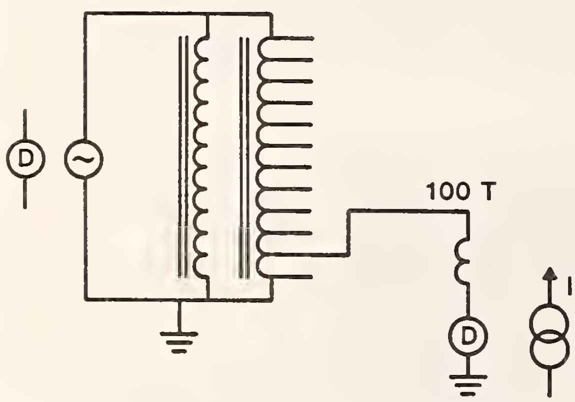


(a) Taps in the secondary winding

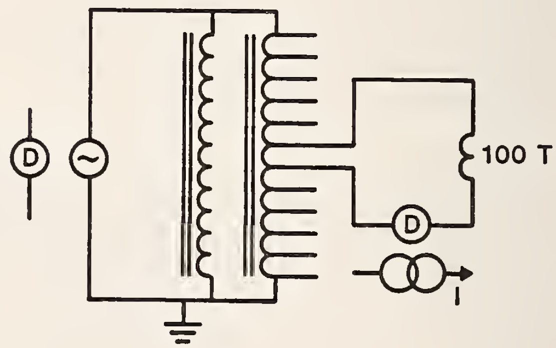


(b) Ratio of two windings

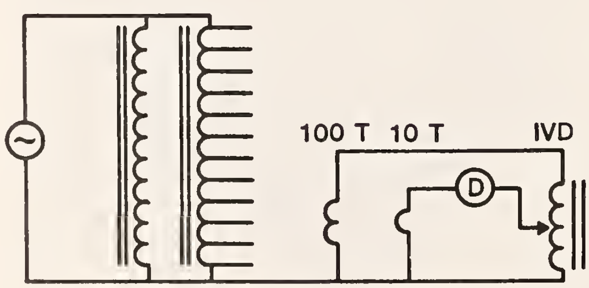
Figure 14. Checking of Two-Stage Transformer Against Inductive Divider



(a) 0.1 tap against 100-T winding



(b) Adjacent taps against 100-T winding



(c) 10-T winding against 100-T winding

Figure 15. Self-Checks of Two-Stage Transformer

4.5 Precision Resistors

The two resistors at the output of the standard current transformer are coaxial shunts of the type shown in Figs. 16 and 17. These shunts were obtained from a commercial source. The shunt consists of a central conductor surrounded by a concentric resistance element of a low-temperature coefficient material. This element is in turn surrounded by a concentric outer conductor. The current is introduced at the male conductor and passes down the inner rod to the junction with the resistor. It then folds back down the resistor and exits via the outer shell of the male connector. The voltage is sampled at the female connector, the center of which is connected through the outer tube to the common end of the resistor. Due to this use of concentric coaxial conductors, the voltage lead is coupled to the resistor in a path which is essentially free of the magnetic field of the current in the resistor. The spacing between the resistor element and the central conductor is kept extremely small to reduce the inductance. The space between the resistor element and the outer shell is filled with a thermal transfer compound, and the outer shell is constructed with an integral heat sink to assist in the control of self heating effects.

These particular units are two-ohm shunts, adjusted to a tolerance of ±400 ppm over a current range of 0 to 2 amperes. Calculation of the reactance of the shunt indicates that the phase shift of the output voltage vs. the input current at 60 Hz should be less than 10 microradians. Calibration confirms that this goal was met.

4.6 Calibration Data

The three principal ratios, 10 A/1 A, 100 A/1 A, 1000 A/1 A, of the standard current transformer were calibrated in the no-load (short circuit) condition and with the tubular two-ohm shunts connected in the secondary and compensation windings. The calibration results are summarized in Table 1; the actual NBS calibration reports are reproduced in Appendix 1. In all cases, the measured ratio and phase angle deviations are within 3 ppm and 4 μrad, respectively. The estimated calibration uncertainties are ±10 ppm and ±10 μrad. Thus the indicated deviations are well within the estimated measurement uncertainties. The equipment that was used to calibrate the standard current transformer is designed for operation primarily in the 0.5 A to 5.0 A range of the secondary current. Hence, the 1.0 A and 0.5 A data in the report are believed to be more reliable than those at lower currents.

The transimpedance of the current transformer-shunt combination was measured for the 100 A/1 A and 1000 A/1 A ratios of the current transformer. The results are tabulated in Table 2. The resistance of the shunt can be calculated from the measured transimpedance and the transformer ratio by using eq. (12) in a slightly modified form,

$$R = (V/I_1)n_1, \qquad (13)$$

where n_1 is the measured complex ratio of the transformer. As the data in Table 2 indicate, the computed phase angle of the shunt is nearly identical and negligible for both sets of measured data. The resistance of the shunt is identical within the resolution of the equipment. It should be noted that the calibration equipment for transimpedance is more accurate in phase angle than that for the transformer ratio [12].

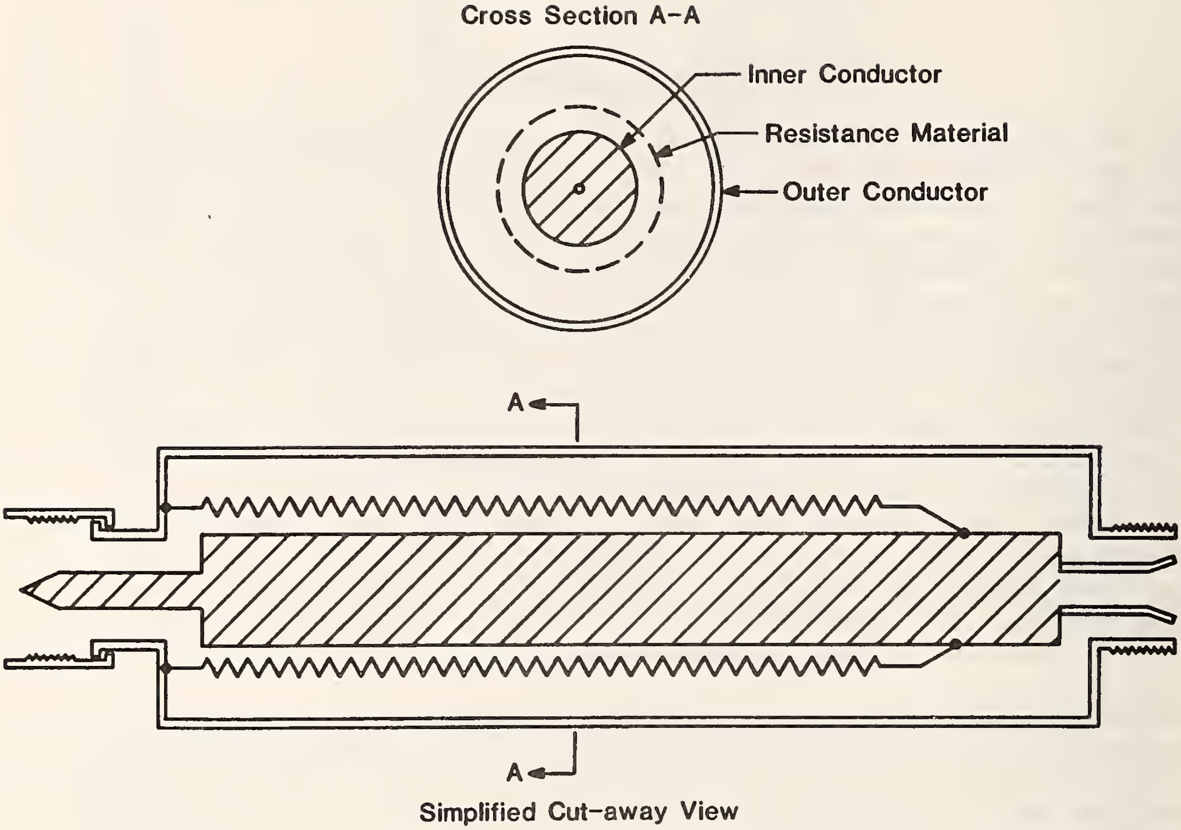


Figure 16. Coaxial Shunts, Cross Section

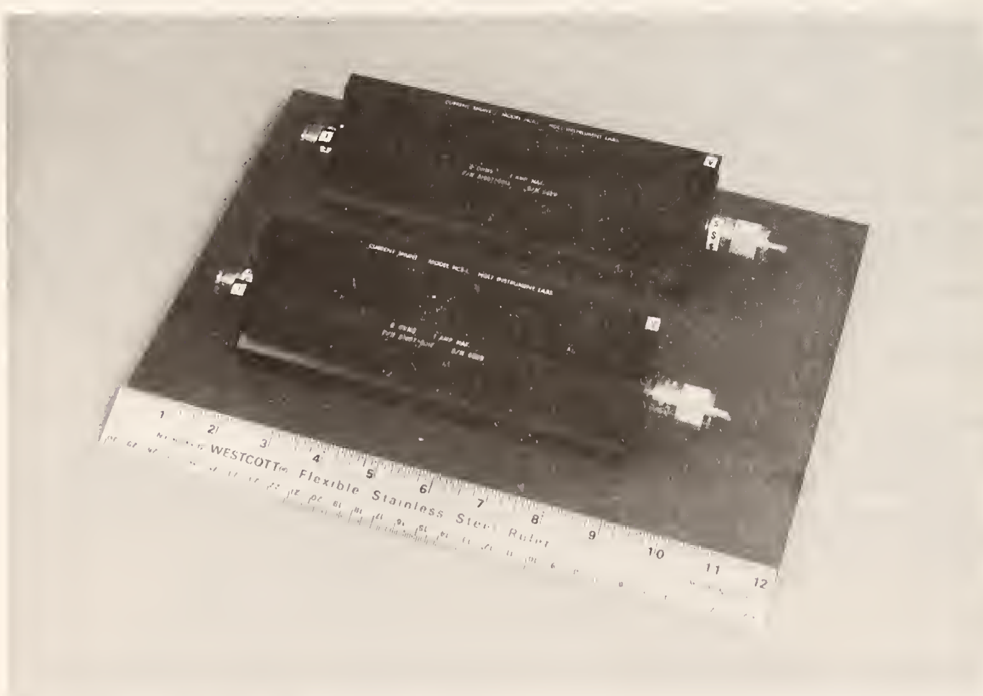


Figure 17. Coaxial Shunts, External View

During the construction of the transformer, the linearity of taps in the secondary winding was measured using a special calibration arrangement. The results are tabulated in Table 3. The corrections are expressed as fractions of the input quantity. To obtain the corrections to the ratio or the output quantity, divide the tabulated corrections by the tap setting. It is noted that all magnitude corrections in ratio are smaller than 1 ppm, except for the 0.1 tap; all phase angle corrections in ratio are smaller than 1 μrad. For the 0.1 tap the phase angle correction is 1.29 μrad.

Table 1

Calibration of Standard Current Transformer

Nominal ratio	Burden resistance (ohms)	Current ratio	Phase angle (microradians)
10/1	0	10 x 1.000000	-1
	2	1.000000	-4
100/1	0	100 x 0.999997	0
	2	0.999997	-3
1000/1	0	1000 x 1.000000	+1
	2	1.000000	-2

Secondary Current = 1A

Estimated uncertainty: $\pm 10 \times 10^{-6}$ in ratio
± 10 μrad in phase angle

Table 2

Calibration of Transimpedance
Standard Current Transformer-Shunt Combination

Nominal Transformer Ratio	Measured transimpedance		Computed impedance of shunt	
	Magnitude (ohms)	Phase angle (microradians)	Magnitude (ohms)	Phase angle (microradians)
100/1	0.01999302	-2.6	1.999296	0.4
1000/1	0.00199930	-1.8	1.99930	0.2

Frequency: 60 Hz

The data in Table 1 is used in computations.

Phase angle is positive if the impedance is inductive.

Estimated uncertainty: $\pm 10^{-4}$ in magnitude of transimpedance
± 5 μrad
in phase angle of transimpedance

Table 3

Calibration of Standard Current Transformer
Taps in Secondary Winding

Tap setting (A)	Magnitude correction (a)	Quadrature correction (b)
0.1	0.06 x 10^{-6}	0.12 x 10^{-6}
0.2	0.06	0.11
0.3	0.06	0.01
0.4	0.06	-0.14
0.5	0.06	-0.30
0.6	0.06	-0.44
0.7	0.06	-0.51
0.8	0.05	-0.49
0.9	0.04	-0.34
0.1*	0.00	0.08

$-I_2/I_1 = V_1/V_2 = A + a + jb$

Tap 0.1* is the auxiliary secondary winding.

Estimated uncertainty: $\pm 0.05 \times 10^{-6}$ in a
$\pm 0.10 \times 10^{-6}$ in b

5. CALIBRATION OF VOLTAGE CHANNEL

5.1 General Approach

The voltage channel of the two test systems is of the type shown in Fig. 1(b). The voltage for the power transducer is generated by means of an active divider incorporating a gas-dielectric, high voltage capacitor and operational amplifier circuits. To obtain the dynamic range over three decades — voltage from 100 V to 100 kV — additional amplifiers and passive networks are utilized to control gain.

For calibration of voltage channels, a standard active divider is employed in the circuit configuration shown in Fig. 18. If the outputs of both active dividers are of the same polarity, an inductive divider and a null detector are inserted between the two dividers as shown in Fig. 18(a). Of interest is the factor n_V by which the primary voltage is reduced in the test system.

$$V_1/n_V = -dV_1(C_1/C_2),$$

$$n_V = -(1/d)(C_2/C_1), \quad (14)$$

where d = inductive voltage divider setting.

Occasionally the amplifiers that follow the integrating stage may be of the inverting type as shown in Fig. 18(b). In such circumstances, either an inverting type buffer amplifier can be inserted between the standard divider and the inductive divider, or the inductive divider can be connected between the two active dividers as in Fig. 18(b). The balance equation becomes

$$n_V = (C_2/C_1)(1-d)/d. \quad (15)$$

As in the case when calibrating the current channel, precautions must be taken in order to avoid errors that could be introduced during the calibration process. Most common measurement problems are caused by improper grounding of various instruments and by electromagnetic interference which could produce erroneous signals in the measurement circuit. Specific precautions mentioned in section 4.1 should be observed when calibrating the voltage channels. An important precaution in using standard high voltage capacitors is to have the low voltage electrode and the conductors leading to it completely shielded.

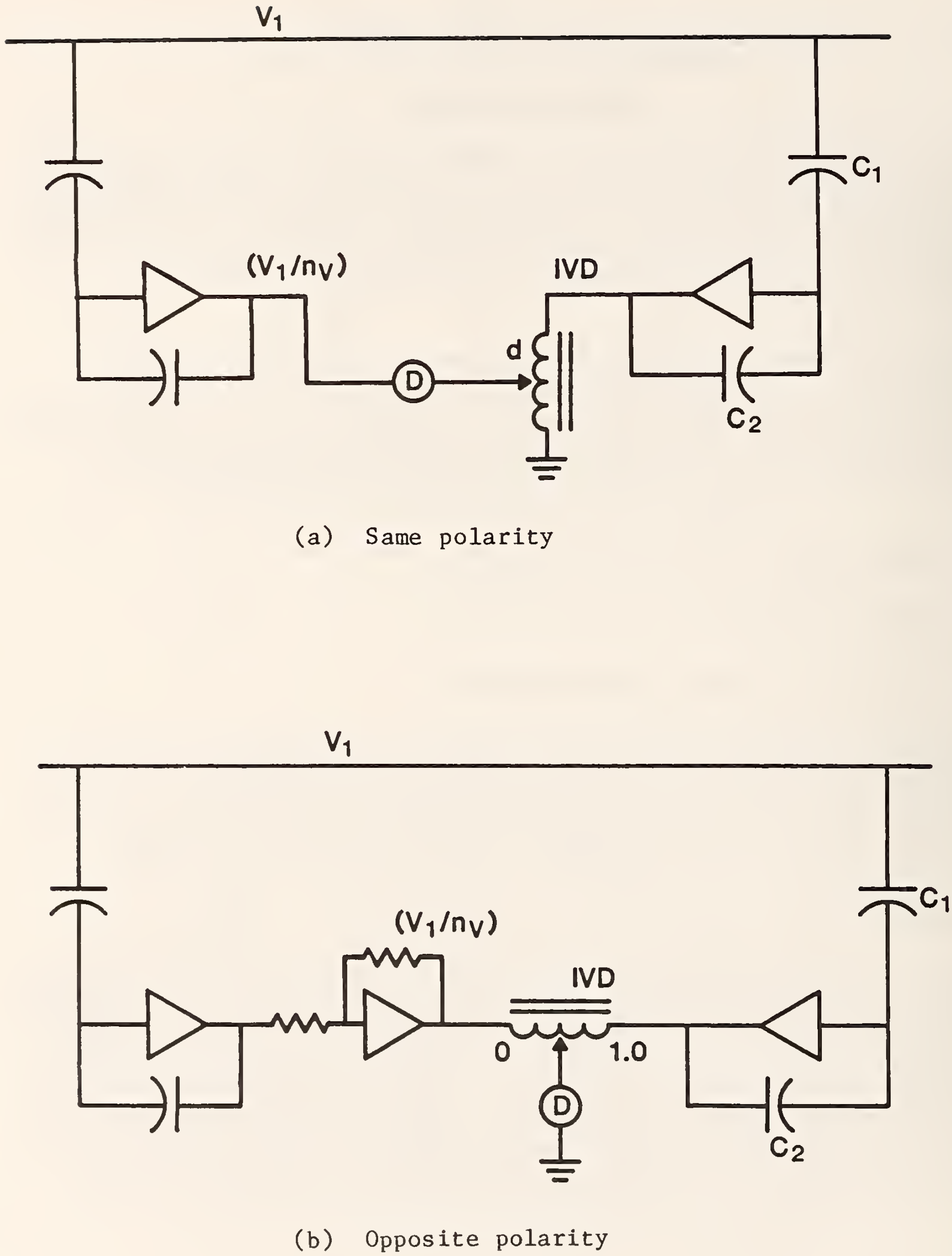


Figure 18. Calibration of Voltage Channel

5.2 Standard Voltage Divider

In developing the standard voltage divider, the goal was to produce an instrument whose voltage ratio depends only on the ratio of the two capacitances, C_1, and C_2, in Fig. 18. The capacitors can be designed to have negligible phase defect, and in-house means can be provided to check the capacitors. The schematic operational amplifier circuit shown in Fig. 18 has imperfections resulting from the finite gain of the amplifier and compensating networks that have to be added to the amplifier to eliminate dynamic instabilities and dc drift. The compensating networks for dynamic stability of high performance amplifiers can become especially complicated [13].

A paper describing a very accurate active divider — both for magnitude and phase angle — that incorporates two gas dielectric capacitors and a magnetic current comparator was recently published [14]. If only the phase angle is of primary importance, a relatively simple solution is possible. A feedback amplifier with low gain and employing a solid-dielectric capacitor in the feedback path is combined with a manually adjusted source that is phase-locked with the high voltage source. The operation of such an instrument is illustrated in Fig. 19. In Fig. 19(a) a capacitive divider is shown having two voltage sources — V_1 is an independent source, while V_2 a source that is phase-locked to V_1 and is manually adjusted in magnitude and phase. The voltage at the junction of the two capacitors is monitored with a null detector which in turn is preceded by a preamplifier. At the null condition, the same current passes in both capacitors and the voltage ratio becomes

$$(V_1/V_2) = -(C_2/C_1). \qquad (16)$$

The need for adjusting V_2 within a few ppm can be avoided by including the preamplifier in the feedback loop as shown in Fig. 19(b). The combined voltage of the controlled source (V_2) and that of the amplifier (V_3) are now applied to C_2. The voltages in this circuit are related as follows:

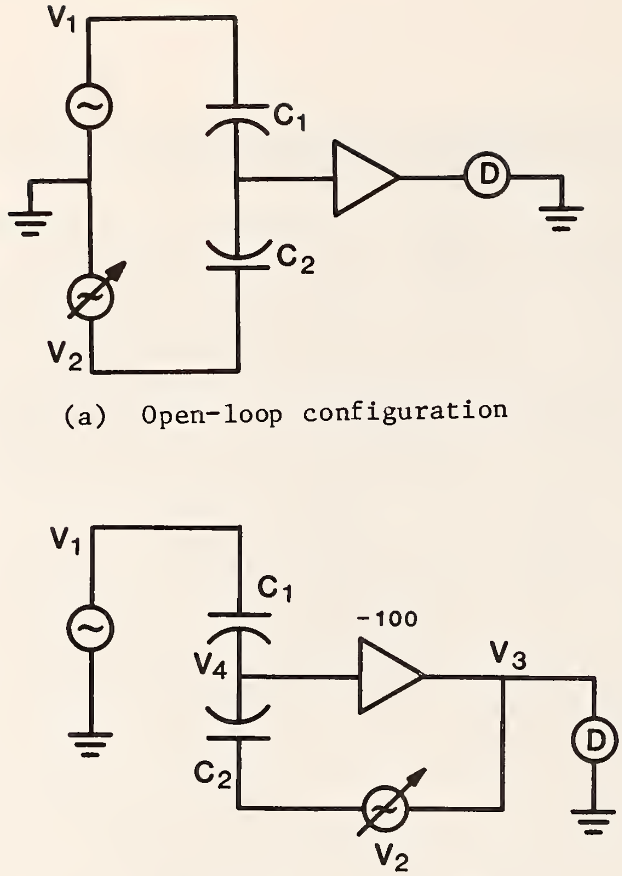
$$(V_1-V_4)C_1 = -(V_2+V_3-V_4)C_2.$$

The ratio of voltages on the two capacitors become,

$$V_1/(V_2+V_3) = -(C_2/C_1)[1-V_4/(V_2+V_3)-(C_1/C_2)V_4/(V_2+V_3)]. \qquad (17)$$

The voltages V_3 and V_4 are related through the gain of the amplifier, which, in this case, is -100. If $V_3 \ll V_2$, the error terms in equation (17) become negligible and the voltage ratio becomes the capacitance ratio as in equation (16). For example, if $V_3 = 0.0001V_2$, the error is 1×10^{-6}.

In practice, there are several possibilities for implementing the controlled source: from a tap of the supply transformer, from another high voltage divider, or from the guard capacitance of the high voltage capacitor. A very stable controlled source can be produced by using a high voltage standard capacitor that has two or more shielded capacitances in the same structure. Commercial units of this type are available. Operational amplifier circuits are employed, as in Fig. 20, to implement the controlled source.



(a) Open-loop configuration

(b) Closed-loop configuration

Figure 19. Active Divider with Controlled Source

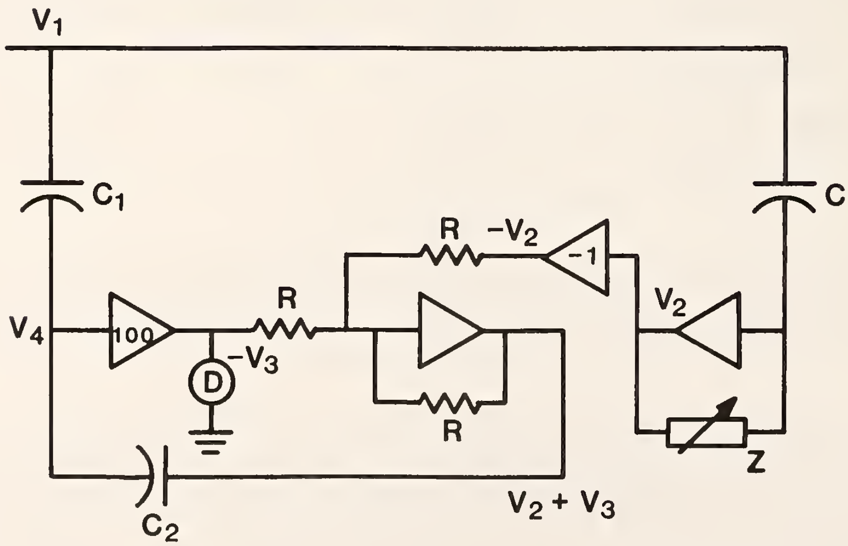


Figure 20. Implementation of Controlled Source in Active Divider

The advantages of the circuit in Fig. 20 are: (1) the voltage at the summing point of the principal amplifier is monitored and, if necessary, can be adjusted to a negligible value; (2) the voltage ratio is the reciprocal of the capacitance ratio, hence, there is no need to calibrate the active divider as a system, only the two capacitors need to be calibrated, primarily for the phase angle; (3) the loop gain of the feedback circuit is 100, hence, there are no problems with dynamic stability; (4) the amplifier comprising the controlled source is not in the feedback loop and does not contribute to dynamic instabilities.

5.3 Standard Capacitor Networks

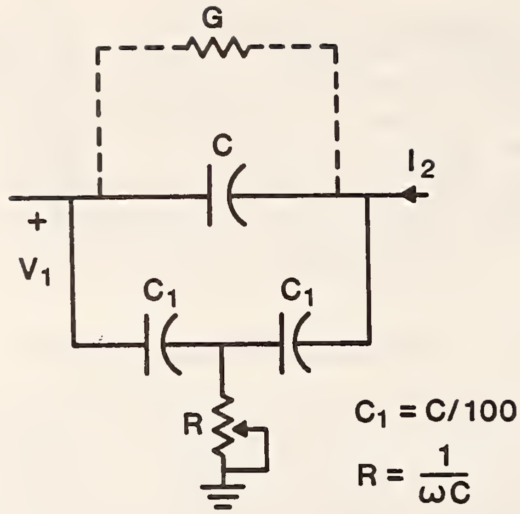
The ratio of the divider critically depends on the ratio of the two capacitances, C_1 and C_2. High accuracy of about ±5 μradians is required for the phase angle, but only a moderate accuracy for the magnitude of about ±0.05%. The high voltage capacitor (100 pF) is a guarded, gas-filled unit. Such capacitors have negligible phase defect and capacitance dependence of temperature that is typically 20 ppm/°C. For this purpose, such a capacitor can be considered as ideal.

To obtain the required output voltages of the active divider, three capacitors, 1.0 μF, 0.1 μF, and 0.01 μF, are required for the low voltage arm. Units having polystyrene film as the dielectric were selected. Their temperature coefficient of capacitance is -0.01%/°C, and the dissipation factor (tangent of the phase angle) ranges from 50 ppm to 100 ppm. No special precautions, except for a moderately accurate calibration, are required for maintaining the capacitance value. The dissipation factor must be measured very accurately and preferably should be compensated. Compensation is feasible, since the three-terminal capacitance rather than the two-terminal capacitance is of importance.

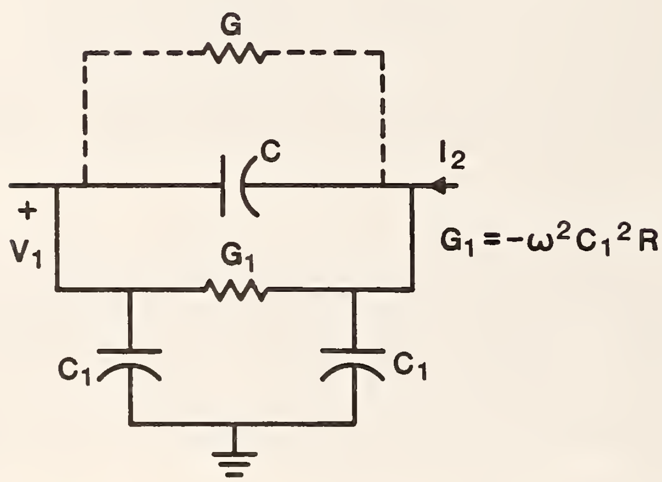
A compensated low voltage capacitor is shown in Fig. 21(a) [15]. C is the value of the actual capacitor, and G is its equivalent loss conductance. The T-network containing the two capacitors and the resistor is the compensating network. The approximate equivalent T-network of the compensating network is shown in Fig. 21(b). The effective negative conductance, G_1, is adjusted to cancel G. The result is that the effective transadmittance becomes equal to the admittance of a pure capacitor,

$$-(I_2/V_1)_{V_2=0} = j\omega C. \qquad (18)$$

The adjustment of the capacitive networks is best accomplished during the calibration of these networks. Since the dissipation factor of the capacitors themselves is very small, typically of the order of 60 ppm, the compensation need not be very precise. Reduction of the effective dissipation factor to within 5 ppm is readily achieved. Preliminary indications are that the compensated dissipation factor remains stable within ±5 ppm. The compensation is for one frequency only. This causes no problem if the calibrations and tests are performed at one power frequency. If the test frequency is changed, e.g., from 60 Hz to 50 Hz, a different setting of the resistor is required.



(a) Circuit diagram



(b) Equivalent circuit

Figure 21. Low Voltage Capacitor Network

The three capacitor networks are enclosed in metal shielding boxes as shown in Fig. 22(a). Two pairs of coaxial terminals are provided — one for the current, the other for the voltage (the current terminals are in back and not visible in Fig. 22(a)). The enclosure containing the electronics for the active divider is shown in Fig. 22(b). The high voltage capacitor is shown in Fig. 4.

5.4 In-House Calibration of Standards

Means for checking the capacitors on site is highly desirable. This applies to both the high-voltage capacitor and the special capacitive networks. Such a capability is established by acquiring one standard 1000-pF capacitor and an impedance bridge. Two impedance bridges are available — one that is based on the inductive divider, the other utilizing the two-stage current transformer.

The inductive divider bridge is shown in Fig. 23(a). It is always operated with the nominal ratio of 1/11. Thus the following comparisons are made: 100-pF (high voltage) vs. 1000-pF (standard); 1000-pF vs. 0.01-μF; 0.01-μF vs. 0.1-μF;0.1-μF vs. 1-μF. The bridge is balanced by adjusting the ratio of the inductive divider. The residual indication on the null detector is the unbalanced phase angle. It should be negligible for the two gas-dielectric capacitors and for the capacitive networks after the loss component has been compensated. When the bridge is balanced,

$$(C_2/C_1) = (1-d)/d, \qquad (19)$$

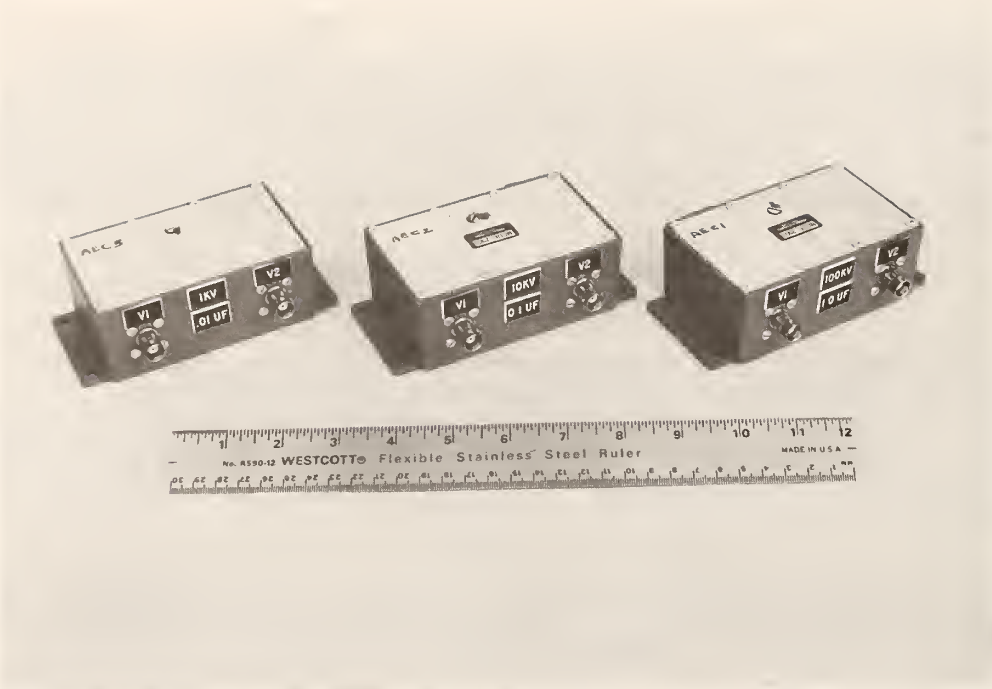
where d is inductive voltage divider setting.

Several precautions are in order. First, the leads from the capacitors to the detector must be completely shielded, especially when calibrating capacitors of low value, e.g, 100 pF to 0.01 μF. Excessive capacitive currents, when passed in the tap of the inductive divider, could cause loading errors. A test can be performed to determine whether such errors are significant by inserting a 10-ohm resistor between the bridge ground and the tap of the inductive divider. The balance should not change. If it does, the capacitive currents can be balanced with the "Wagner ground," consisting of the resistive divider and the capacitor connected to its tap. Second, when measuring large capacitances, 0.1 μF and 1.0 μF, the leads should be short so that the lead impedances do not add significantly to the impedances of the capacitors and the inductive divider. Fig. 23(b) is the suggested circuit for comparing the two largest capacitors; it incorporates the features of a Kelvin bridge.

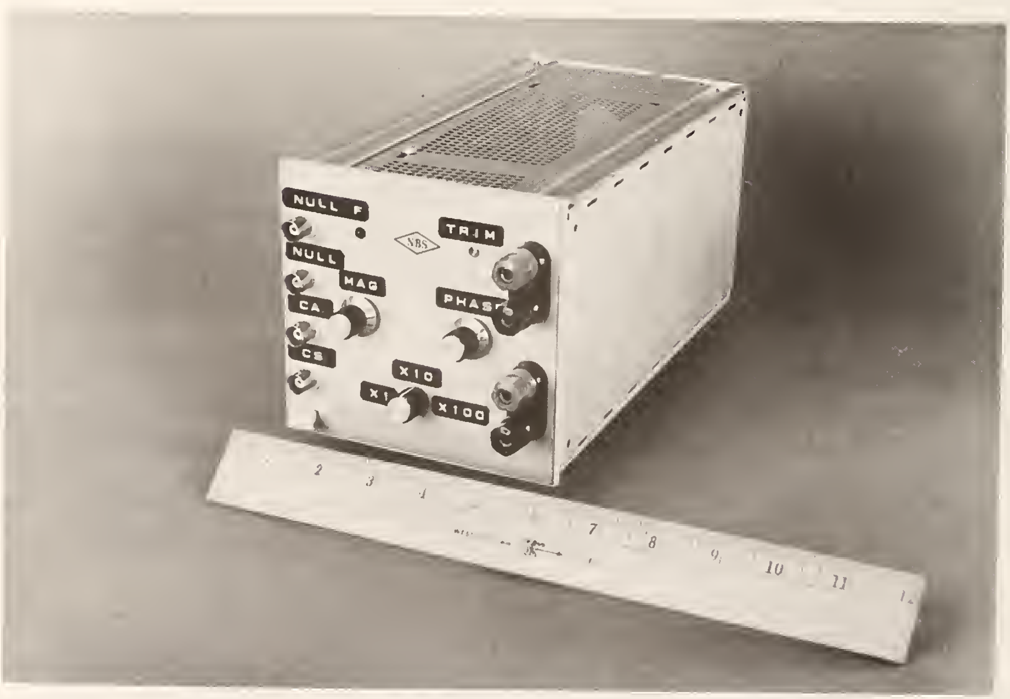
Greater accuracy can be obtained by using the standard current transformer in an impedance bridge configuration as shown in Fig. 24. The compensation winding now consists of a series connection of the 1000-turn and 100-turn windings. This combined winding is connected to the source and to the current terminals of the series connection of the two capacitors. The 1000-turn secondary winding and the 100-turn primary winding are also connected in series and then to the potential terminals of the two capacitors. The inductive divider, connected to the 100-turn auxiliary secondary winding, and C_3, provides the magnitude adjustment. At balance,

$$(C_2/C_1) = (N_2/N_1)(1+0.01d), \qquad (20)$$

where d = inductive voltage divider setting.

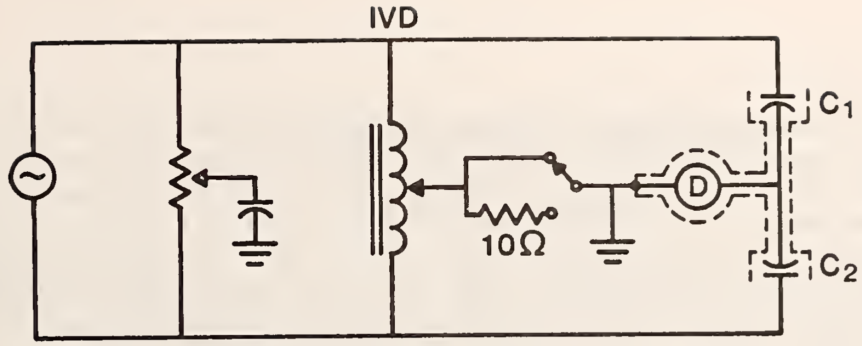


(a) Low voltage capacitor networks

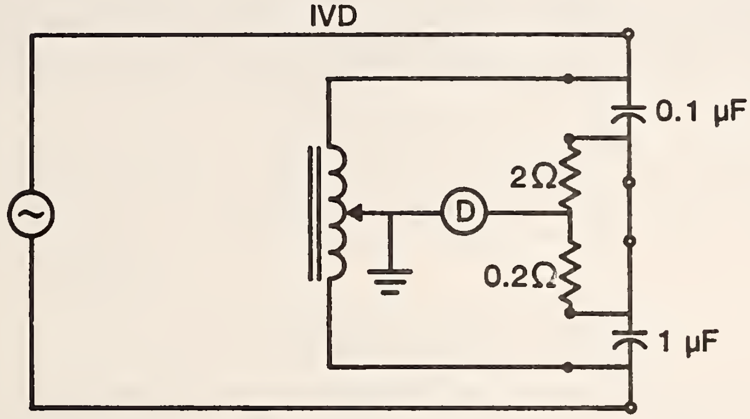


(b) Enclosure containing electronics

Figure 22. Components of Active Divider



(a) Comparison of small capacitors



(b) Comparison of large capacitors

Figure 23. Capacitance Bridge Based on Inductive Voltage Divider

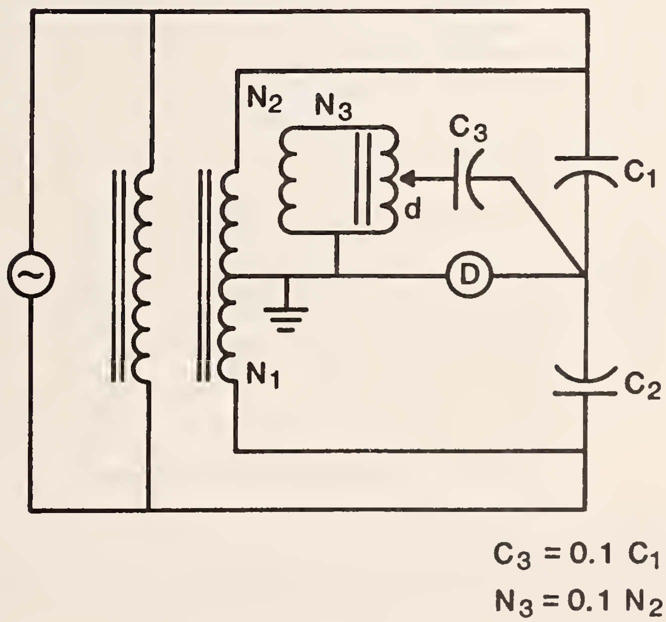


Figure 24. Capacitance Bridge Based on Two-Stage Current Transformer

In general, the inductive divider bridge is easier to use but is not as accurate as the two-stage transformer bridge because of inherent uncertainties of the divider. The inductive divider bridge is an excellent instrument for monitoring the performance of the capacitors after the initial high-accuracy calibration has been performed by other means. The three capacitor networks, before calibration at NBS, were adjusted with the inductive divider bridge. Good results were achieved with residual deviations in the dissipation factor of 6×10^{-6}, -13×10^{-6}, and 0. The inductive divider bridge itself can be calibrated at fixed points, including the 11/1 ratio, by using the transformer bridge as in Fig. 14(a).

The current transformer bridge can yield phase angle uncertainties that are within 3 μrad in each measurement. Thus, even with three measurements involved in the buildup process, the overall uncertainty can be maintained within ±9 μrad.

6. CALIBRATION OF POWER TRANSDUCERS

6.1 Standard Transducer

The power transducers in the two test systems are of the time division multiplier type that multiply and average two voltages (or a voltage and current) [16]. For their calibration, a special higher accuracy time division multiplier was purchased commercially. This standard transducer was calibrated at NBS against a dual-channel signal source which serves as a phase angle standard [17]. The calibration results given in Appendix 1 indicate that the corrections of the transducer are within one percent (except for one point) of the full-scale reading for the three ranges of the power factor -- 1.0, 0.1, and 0.01. The manufacturer's specified uncertainty limit is also ±1% for the three ranges of the power factor. The calibration at NBS had an uncertainty of ±0.2% for the magnitude and ±50 μrad for the phase angle. To realize the highest accuracy in the calibration of the transducers in the test systems, the corrections for the errors of the standard transducer had to be applied. This approach is adequate; however, a standard with negligibly small corrections that could be resolved into magnitude and phase angle components would be more desirable.

6.2 Standard Phase Shifter

A very promising type of calibrator for transducers operating at small power factor is an accurate 90 degree phase shifter. Such a device was developed and constructed in the later stage of the project, but it was not available during the alignment of the test systems.

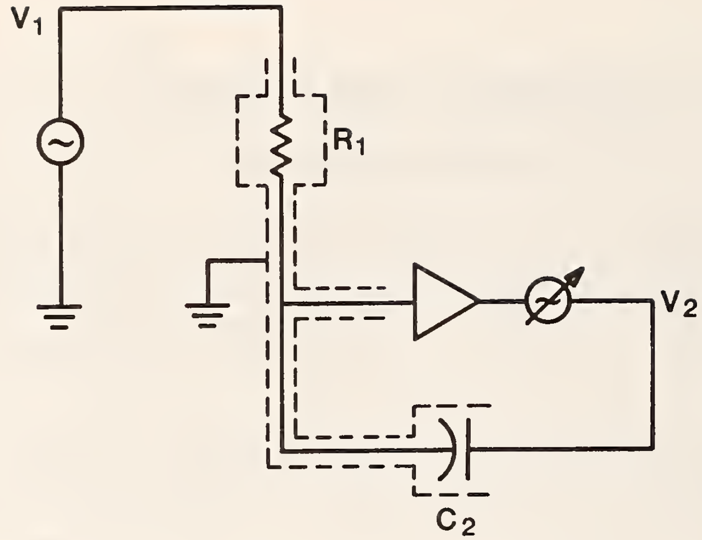
An accurate yet simple 90 degree (or near 90 degree) phase shifter is obtained by converting the active divider described in section 5.2 and shown in Fig. 19 into an integrator shown in Fig. 25. The input element is a 26.5 kΩ miniature metal film resistor. The feedback element is the 0.1-μF special capacitance network used with the active divider. The estimated phase angle error limit for the resistor is ±5 μrad, assuming a stray capacitance of 0.5 pF due to the resistor itself and the electrostatic shielding enclosure. All the other phase angle errors are as in the active divider. The combined effect is estimated not to exceed ±20 μrad. The controlled source shown in Fig. 25 is implemented by a circuit that is analogous to that of Fig. 20.

Calibration of a transducer is outlined in Fig. 25(b). The input and output voltages of the phase shifter are applied to the transducers, and the magnitudes of voltages are measured with precision digital voltmeters. To provide nominal power factors of 0.01, 0.02, 0.05, and 0.1, C_2 can be shunted with the four resistors as shown. Output of the transducer is

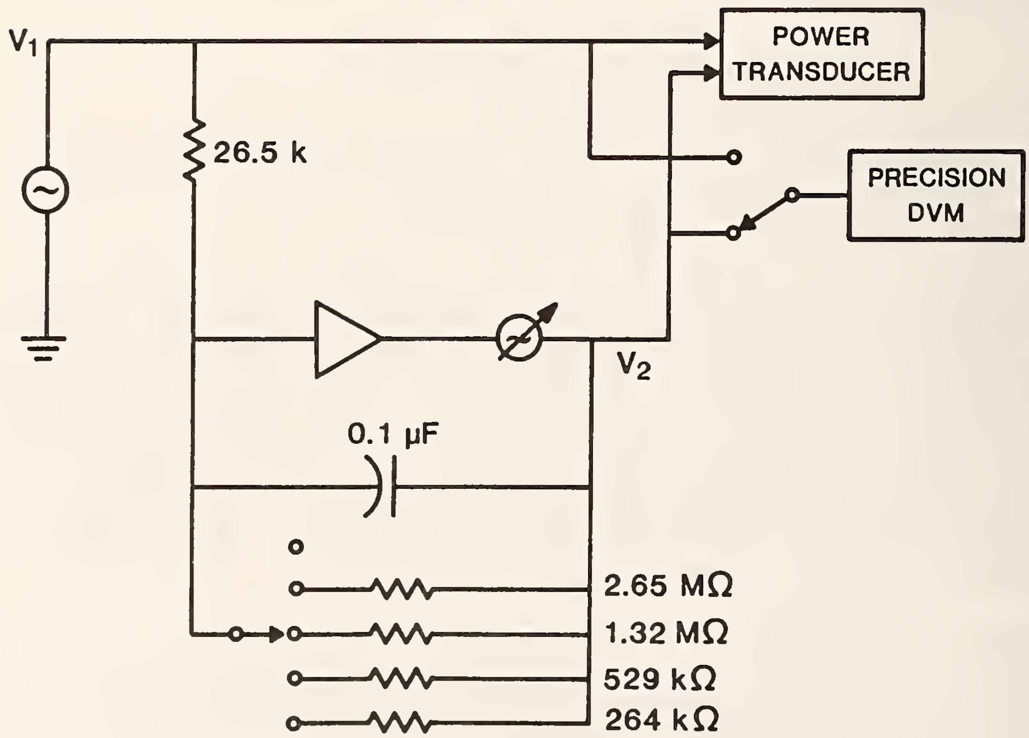
$$P = kV_1V_2 \cos \Theta \tag{21}$$

where $\Theta = \tan^{-1}(\omega RC)$,
k has the dimension of siemens

Lagging power factor is obtained by interchanging the connections at the transducer. It is to be noted that for the feedback resistors it is important to know accurately their resistance values, not their phase angles.



(a) For zero power factor



(b) For power factors of 0.00, 0.01, 0.02, 0.05, and 0.1; shielding omitted

Figure 25. Active Phase Shifter

7. ALIGNMENT OF TEST SYSTEMS

7.1 Test System 1

Figure 26 shows a schematic representation of the circuit used in the alignment of the current channel. The input signal to the buffer amplifier is nominally 5 volts, corresponding to the primary currents of 10 A, 100 A, 1000 A, and 10,000 A. Nominal voltage is achieved by changing the burdens in the secondary windings of the zero-flux current transformer. The buffer amplifier has a fixed gain of two. Small in-phase and quadrature currents can be injected in the feedback loop of the amplifier in order to produce small adjustments in gain. The scaling amplifier reduces the signal to approximately one volt.

The gain of the buffer amplifier is adjusted for the 100-ampere primary current. For other currents, the gain of the current channel is aligned by small ajustments in the burdens of the current transformer. The general procedure outlined in section 4.1 is followed for the alignment of the current channel.

It is to be noted that the gain of the current channel is not trimmed for all the settings of the scaling amplifier. However, as the gain of this amplifier is changed, the resulting phase angles remain relatively stable within ± 20 μrad; the changes in the magnitude are larger, approaching $\pm 0.1\%$.

Still larger changes are observed due to nonlinearities of the zero flux current transformer. The adjustments are made to produce the smallest overall error in a particular range of the primary current. After the adjustment, the residual phase angle and magnitude errors were determined at the full scale points and 50% of the full scale points. The results are given in Table 4. These residual errors are included in the assessment of the uncertainty of the test system, as discussed in section 8.

Adjustment of the voltage channel is a two-step procedure. Initially the buffer and ranging amplifiers are adjusted in the circuit of Fig. 27. The final adjustment, for phase angle only, is accomplished by using the circuit of Fig. 28. Adjustments are made for three full-scale voltage ranges — 1 kV, 10 kV, and 100 kV. Thus, three separate trimming circuits are provided for the ranging amplifier. The general procedure for alignment described in Section 5.1 is followed.

As for the current channel, different gain settings of the scaling amplifier, residual pickup and nonlinearities in the test system prevented alignment of the voltage channel over the entire operating range. The magnitudes and phase angles were adjusted to yield the lowest practical error in a particular range. The residual phase angle and magnitude errors are tabulated in Table 5.

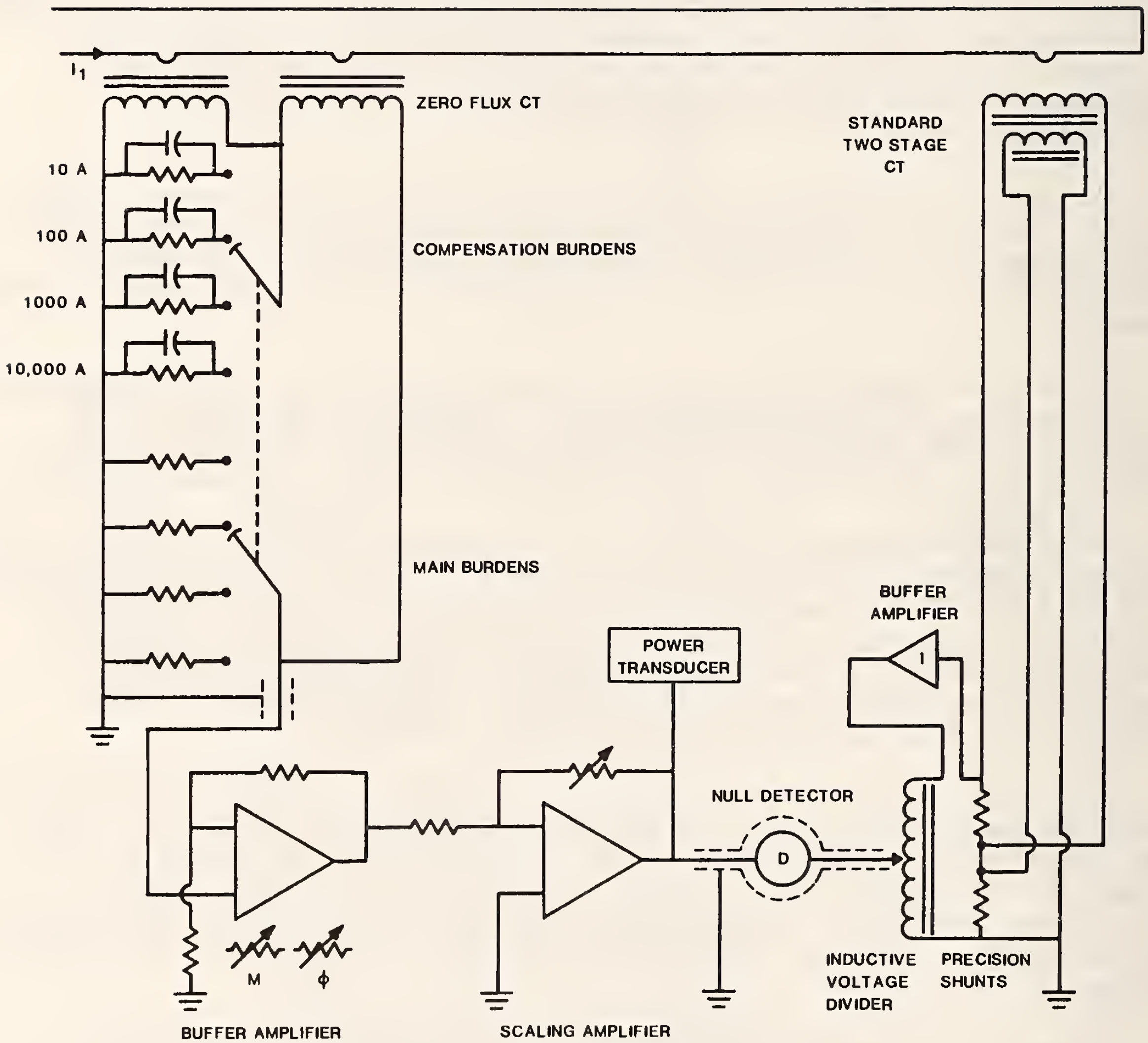


Figure 26. Current Channel Alignment, Test System 1

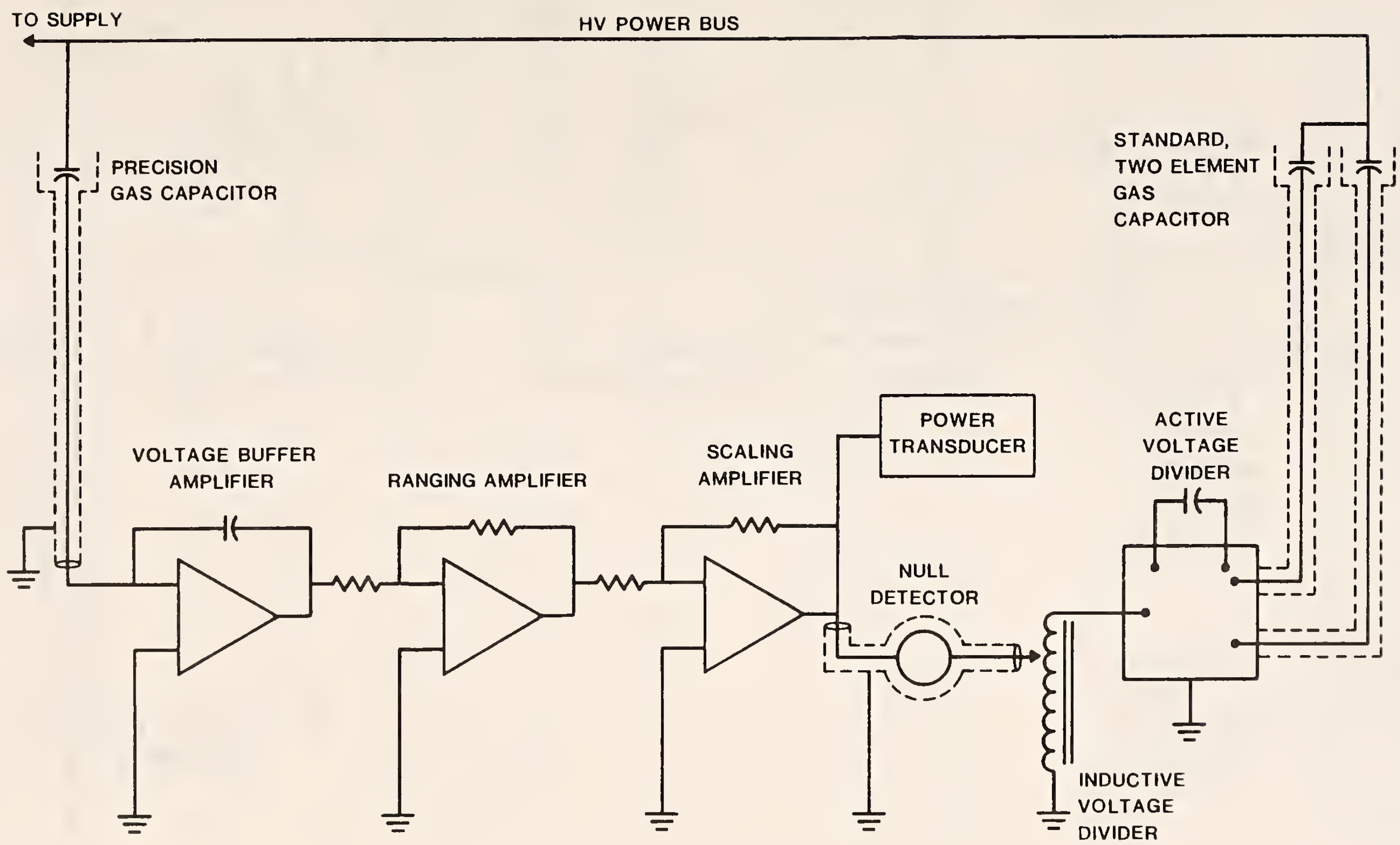


Figure 27. Voltage Channel Alignment (Coarse), Test System 1

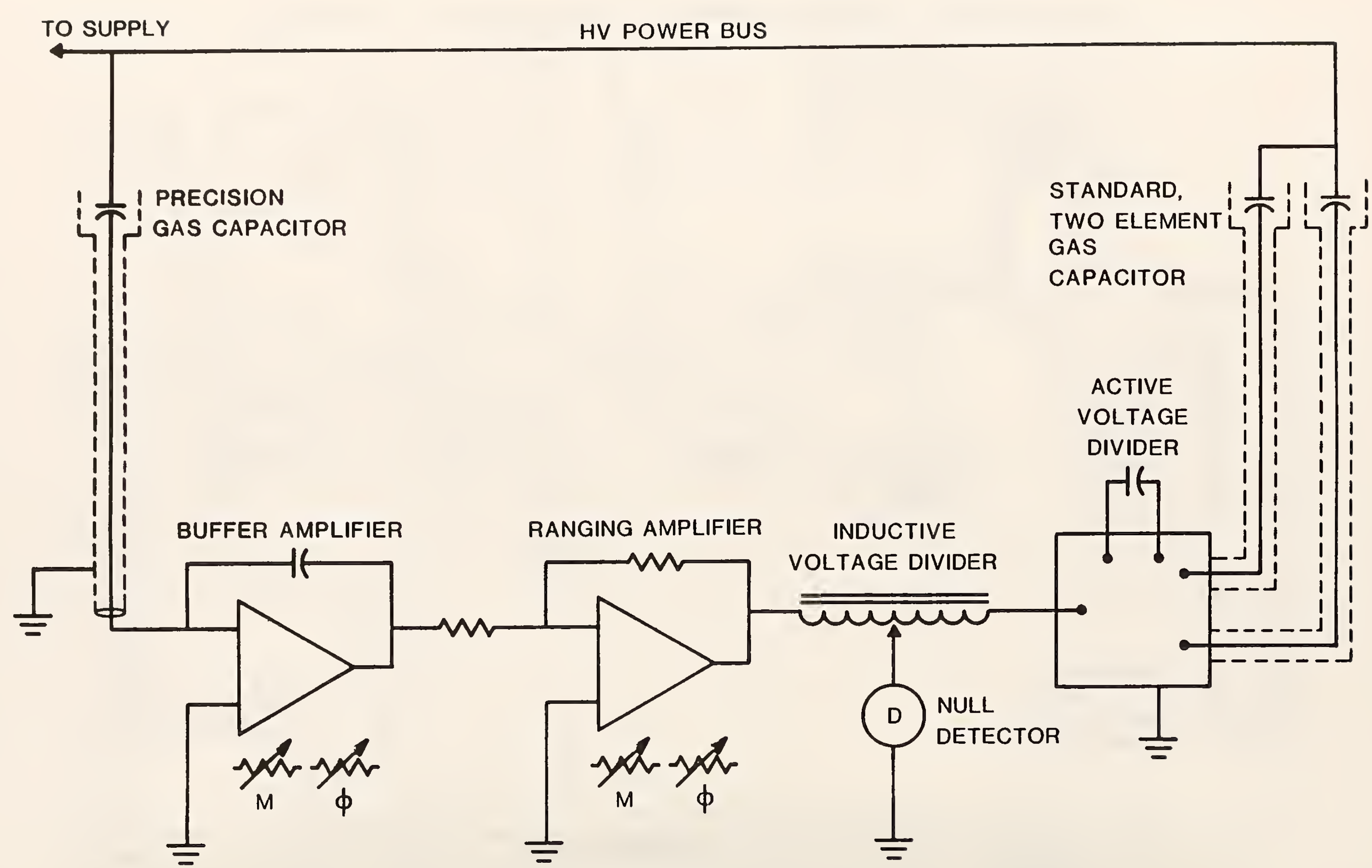


Figure 28. Voltage Channel Alignment (Fine), Test System 1

The third critical subsystem is the power transducer and its associated circuitry. In order to obtain high accuracy in power measurements at low power factors, great care must be exercised in selecting this subsystem. Special transducers for low power factor applications have to be utilized. The original time-division-multiplier-type transducers were replaced with improved units of the similar type that were fabricated at ASEA Electric.

Transducers are most accurate near their full-scale values. Hence, scaling amplifiers are employed that maintain the two input signals between 0.7 of full-scale and full-scale, yielding an output signal that is no lower than 0.5 of full-scale. To maintain a direct reading feature for the entire power measuring system, scaling amplifiers are used also at the output of the transducer, but the gains of these amplifiers are reciprocals of the gains of the input amplifiers.

The transducers in the test system are aligned using the circuit of Fig. 29. Dual-channel, variable-phase source supplies two signals to the transducer under test and to the standard transducer that was calibrated at NBS. Adjustments are made in the system transducer to minimize its deviation from the correct value. Because of residual nonlinearities, perfect alignment could not be made over the entire measurement range. The largest residual errors for three power factors are tabulated in Table 6.

7.2 Test System 2

The general principles for aligning this test system are similar to those of system 1. Hence, the circuit diagrams are not repeated.

The current channel in this test system contains a two-stage current transformer with a fixed turns ratio of 10,000/1. The secondary current is passed to an operational amplifier that acts as a current-to-voltage converter. Four ranges of conversion are provided, corresponding to full-scale primary currents of 1 A, 10 A, 100 A, and 1000 A. The buffer amplifier was modified from the original design to provide noninteractive magnitude and phase angle adjustment for each of the four ranges.

As for test system 1, adjustments were made to minimize the error in the entire range. The residual errors are tabulated in Table 7.

The voltage channel is aligned by a procedure that is similar to that utilized with test system 1. The residual errors are tabulated in Table 8.

The power transducer circuit was modified by the addition of scaling amplifiers. The calibration and alignment are similar to those employed with test system 1. The results are given in Table 9.

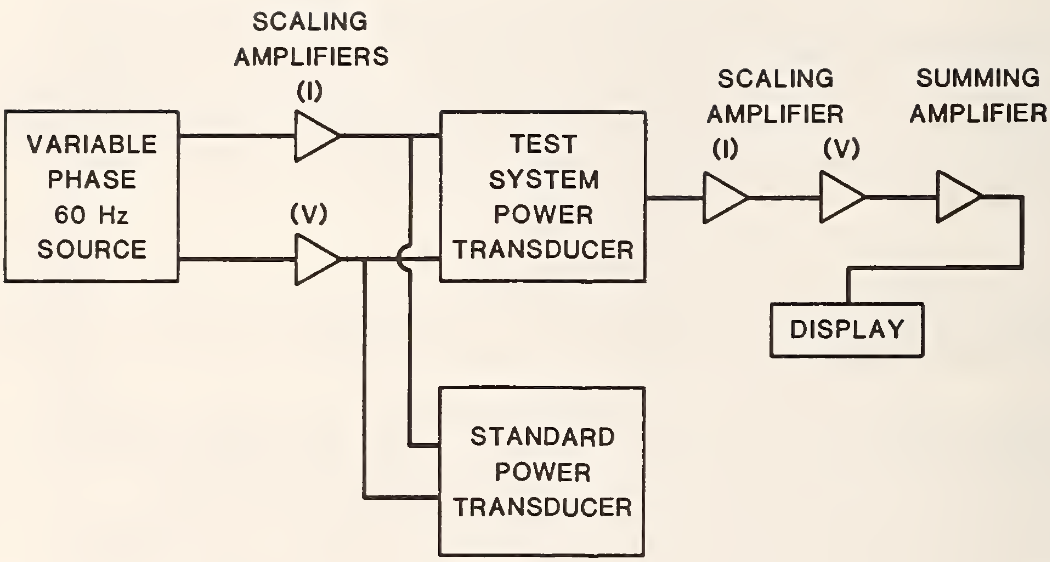


Figure 29. Power Transducer Alignment, Test System 1

Table 4

Current Channel Alignment

Test System 1

Primary current (A)	Phase angle error (μrad, absolute value)		
	Aϕ	Bϕ	Cϕ
5	38	55	34
10	70	52	69
50	37	6	6
100	96	75	92
500	28	13	34

Magnitude error, absolute value
average: 0.13%
maximum: 0.34%

Table 5

Voltage Channel Alignment

Test System 1

Primary voltage (kv)	Phase angle error (μrad, absolute value)		
	Aϕ	Bϕ	Cϕ
0.5	13	25	106
1.0	25	6	100
5.0	4	6	6
10.0	40	20	26
40.0	75	80	40

Magnitude error, absolute value
average: 0.10%
maximum: 0.42%

Table 6

Power Transducer Alignment

Test System 1

Power factor (lagging)	Error in power (percent of reading)			
	Aϕ	Bϕ	Cϕ	3ϕ
1.00	0.00	+0.03	0.00	+0.01
0.10	+0.11	+0.02	+0.01	+0.05
0.01	+0.64	-0.025	+0.04	+0.22

Table 7

Current Channel Alignment

Test System 2

Primary current (A)	Phase angle error (μrad, absolute value)		
	AΦ	BΦ	CΦ
0.5	10	10	20
1	15	30	15
5	5	3	2
10	3	4	3
50	10	4	16
100	10	5	10
500	8	5	6

Magnitude error, absolute value
average: 0.16%
maximum: 0.27%

Table 8

Voltage Channel Alignment

Test System 2

Primary voltage (kV)	Phase angle error (μrad, absolute value)		
	AΦ	BΦ	CΦ
0.5	3	5	4
1.0	3	3	3
5.0	4	4	4
10.0	2	3	3
50.0	20	20	20

Magnitude error, absolute value
average: 0.10%
maximum: 0.20%

Table 9

Power Transducer Alignment

Test System 2

Power factor (lagging)	Error in power (percent of reading)			
	AΦ	BΦ	CΦ	3Φ
1.00	-0.04	+0.22	+0.19	+0.12
0.10	+0.50	+0.73	+0.71	+0.65
0.01	+0.81	+0.62	+0.03	+0.49

8. ANALYSIS OF MEASUREMENT ERRORS

8.1 General Comments

Errors or uncertainties in transformer loss measurements are contributed by numerous sources. Several authors in the past have discussed the nature of these errors [18,19,20]. General guidelines for expressions of errors are well established; a comprehensive summary is available in [21].

The propagation of errors in the measurement of power is apparent from the general equation for power under sinusoidal conditions

$$P = VI \cos \Theta. \qquad (22)$$

Taking the partial derivatives of (22) yields,

$$\partial P = (I \cos \Theta)\, \partial V + (V\cos \Theta)\partial I - (VI \sin \Theta)\partial\Theta. \qquad (23)$$

Dividing (23) by (22),

$$\partial P/P = \partial V/V + \partial I/I - \tan \Theta\, \partial\Theta. \qquad (24)$$

Equation (24) indicates how small changes in voltage, current, and phase angle combine to produce changes in power. While relative changes in the magnitude of V and I enter directly as changes in power in an additive manner, the change in phase angle in radians is modified by the tangent of the phase angle. For phase angles approaching $\pi/2$ rad (small power factors, <0.1), $\tan \Theta \approx \pm 1/\cos \Theta$, and therefore equation (24) becomes,

$$\partial P/P = \partial V/V + \partial I/I \mp \partial\Theta/\cos\Theta. \qquad (25)$$

When dealing with errors, it is customary to substitute incremental changes in (24) and (25) for infinitesimal changes. Also a ($\pm$) sign is used since the errors can be positive or negative. Thus, the equation for propagation of errors in power measurement for small power factors becomes,

$$\Delta P/P = \pm\Delta V/V \pm \Delta I/I \mp \Delta\Theta/\cos\Theta. \qquad (26)$$

The first two terms on the right of equation (26) are known as the magnitude errors; the third term is the phase angle error. Each critical subcomponent in the measurement system must be assessed for the two types of errors. In the case of voltage and current scaling devices, all three components are separately identifiable. In the case of the power transducer, the two magnitude components are inherently combined, if the terminal characteristics of the instrument are considered.

From the discussion in the previous paragraphs, the error in power measurement at low power factors can be formalized as follows,

$$P_t = P_i(1 \pm a \pm b/\cos \Theta), \qquad (27)$$

where

P_t is the true power,
P_i is the indicated power,
a is the fractional magnitude error, and
b is the phase angle error in radians.

When dealing with error components, it is frequently awkward to use simple fractions. It is much more convenient to express such values in terms of percent, parts per thousand, or parts per million. It is important that similar units of value are used for b as for a, e.g., centiradians, milliradians, microradians.

Both error components, a and b, have contributions from numerous sources. The methods for combining the contributions are reviewed in the text that follows. The uncertainties in a measurement process arise from lack of precision (random errors) and possible offsets or biases (systematic errors). The random errors can be determined rigorously from the measurement results; they are amenable to the treatment by statistical methods and are described by such measures as standard error, probable error, and confidence interval. The effect of random errors can be reduced by increasing the number of replicate measurements and taking the mean of the increased set of measurement data.

The assessment of systematic errors is a more difficult and more subjective process. Quoting from reference 21:

> "Although a general guideline for the approach to the assessment of systematic uncertainties can be formulated, there are, unfortunately, no rules to objectively assign a magnitude to them. For the most part, it is a subjective process. Their magnitudes should preferably be based on experimental verification, but may have to rely on the judgment and experience of the metrologist. In general, each systematic uncertainty contribution is considered as a quasi-absolute upper bound, overall or maximum limit on its inaccuracy. Its magnitude is typically estimated in terms of an interval from plus to minus δ about the mean of the measurement result. By what method then should the magnitude of these maximum limits be assigned? It may be based on comparison to a standard, on experiments designed for the purpose [4], or on verification with two or more independent and reliable measurement methods. Additionally, the limits may be based on judgment, based on experience, based on intuition, or based on other measurements and data. Or the limits may include combinations of some or all of the above factors. Whenever possible, they should be empirically derived or verified. The reliability of the estimate of the systematic uncertainty will largely depend on the resourcefulness and ingenuity of the metrologist."

In estimating various systematic errors, different approaches appropriate to each individual error are utilized: direct calibration and experimental verification, published data on the stability of components and materials, design data, and experience with similar standards.

Several methods are used for combining the component errors to obtain the overall uncertainty. The following two are the most commonly used.

(a) combine linearly the random error at a certain accepted confidence level and all systematic errors,

(b) combine the systematic errors in quadrature (as the square root of the sum of squares, rss), and add linearly the result to the random error.

The first approach tends to overestimate the error, but it does represent a quasi-absolute upper bound for the overall error, even if the probability of reaching this upper bound is small. The second approach yields an estimated upper bound which is considerably smaller than the maximum possible limit, if several component errors of similar magnitude are combined. This method appears to be favored in engineering-type measurements [22,23].

The next three sections summarize the estimated measurement errors for the two test systems as well as for the standard system. The latter consists of the standard current transformer and shunt, the standard voltage divider, and the standard power transducer. The standard system was used for loss measurement on transformers on single phase basis and, thus, for direct verification of test system 1. In all cases the random errors are much smaller than the systematic errors; hence, the former are neglected.

8.2 Standard System

The errors relating to components of the standard system are summarized in Table 10. In Tables 11, 12, and 13, the errors of the components are combined to yield the overall errors for the measurement of current, voltage, and power. In power measurement, the error in current and voltage channels include the contributions from all the components listed in Tables 11 and 12, except the rms voltmeter.

A current interaction term is added in Table 13. It is twice the error of the current measuring instrument which, in this case, is the rms voltmeter. The interaction term does not include the error of the current channel, which is common to both the current and power measuring instruments and, therefore, does not contribute an additional error. The interaction term is required because the load loss is determined and reported as a function of the test current.

Using the data in Table 13, combined errors are calculated for several power factors. They are tabulated in Table 14 and plotted in Fig. 30. It should be added that the data in Table 13 are also applicable for calculating the error in the measurement of no-load power loss. Instead of the current interaction term, the voltage interaction term has to be used.

Table 10

Errors of Components of
Standard System

Component	Magnitude error (ppm)	Phase Angle error (μrad)
Two-stage CT and shunt	100	8
1000-pF standard capacitor	25	5
100-pF HV capacitor	100	5
LV capacitor networks	500	5
Inductive voltage divider	5	10
RMS voltmeter	120	—
Power transducer	2000	50

Table 11

Errors in Current Measurement
Standard System

Source of error	Magnitude error (ppm)	Phase angle error (μrad)
CT and shunt	100	8
IVD	5	10
RMS voltmeter	120	—
RSS error	156	13
Maximum error	225	18

8.3 Test System 1

The errors in power measurement of test system 1 are summarized in Table 15. They include the contributions from the standard system as well as residual deviations of the test system after the alignment had been done. For the magnitude and phase angle errors of the current and voltage channels, the largest values from the Tables 4 and 5 are selected. For the errors of the power transducer the largest three-phase average is selected from Table 6. The errors for several typical low power factors are tabulated in Table 16 and plotted in Fig. 31.

8.4 Test System 2

The errors of test system 2 are summarized in Tables 17 and 18 and are plotted in Fig. 32. The method of selecting various error components is the same as that for test system 1.

Table 12

Errors in Voltage Measurement
Standard System

Source of error	Magnitude error (ppm)	Phase angle error (μrad)
HV capacitor	100	5
LV capacitor networks	500	5
Active divider summing point	—	7
IVD	5	10
RMS voltmeter	120	—
RSS error	524	14
Maximum error	725	27

Table 13

Errors in Power Measurement
Standard System

Source of error	RSS error		Maximum error	
	Magnitude (a) (ppm)	Phase angle (b) (μrad)	Magnitude (a) (ppm)	Phase angle (b) (μrad)
Current channel	100	13	105	18
Voltage channel	510	14	605	27
Power transducer	2000	50	2000	50
Current interaction effect	240	—	240	—
TOTAL	2080	54	2950	95

Table 14

Combined Errors in Power Measurement
Standard System

Power factor cosθ	RSS error			Maximum error		
	a (%)	b/cos θ (%)	Total (%)	a (%)	b/cos θ (%)	Total (%)
0.01	0.21	0.54	0.58	0.30	0.95	1.25
0.02	0.21	0.27	0.34	0.30	0.48	0.78
0.05	0.21	0.11	0.24	0.30	0.19	0.49
0.10	0.21	0.05	0.22	0.30	0.10	0.40
0.20	0.21	0.03	0.21	0.30	0.05	0.35

$$P_t = P_i\ (1 \pm a \pm b/\cos\ \theta)$$

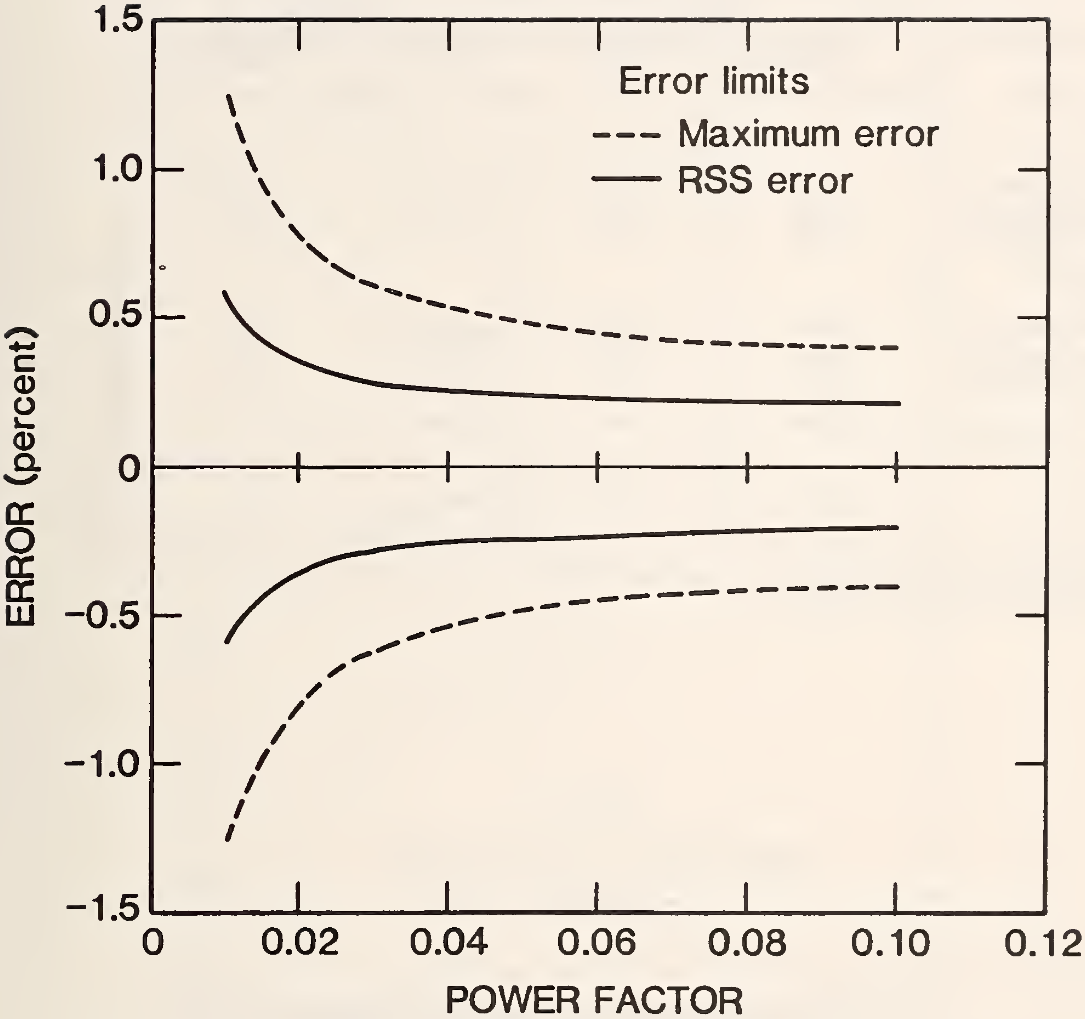


Figure 30. Standard System, Limits of Errors

Table 15

Errors in Power Measurement

Test System 1

Source of error	RSS error		Maximum error	
	Magnitude (a) (ppm)	Phase angle (b) (μrad)	Magnitude (a) (ppm)	Phase angle (b) (μrad)
Standard				
Current channel	100	13	105	18
Voltage channel	510	14	605	27
Power transducer	2000	50	2000	50
Test system				
Current channel	3400	96	3400	96
Voltage channel	4200	106	4200	106
Power transducer	2200	—*	2200	—*
Current interaction	2000	—	2000	—
TOTAL	6,505	153	14,510	297

*In calibrating the power transducers in the test system, the contributions from magnitude and phase angle errors are conbined.

Table 16

Combined Errors in Power Measurement

Test System 1

Power factor cosΘ	RSS error			Maximum error		
	a (%)	b/cos Θ (%)	Total (%)	a (%)	b/cos Θ (%)	Total (%)
0.01	0.65	1.53	1.66	1.45	2.97	4.42
0.02	0.65	0.765	1.00	1.45	1.48	2.93
0.05	0.65	0.31	0.72	1.45	0.59	2.04
0.10	0.65	0.15	0.67	1.45	0.30	1.75
0.20	0.65	0.08	0.65	1.45	0.15	1.60

$$P_t = P_i \, (1 \pm a \pm b/\cos\Theta)$$

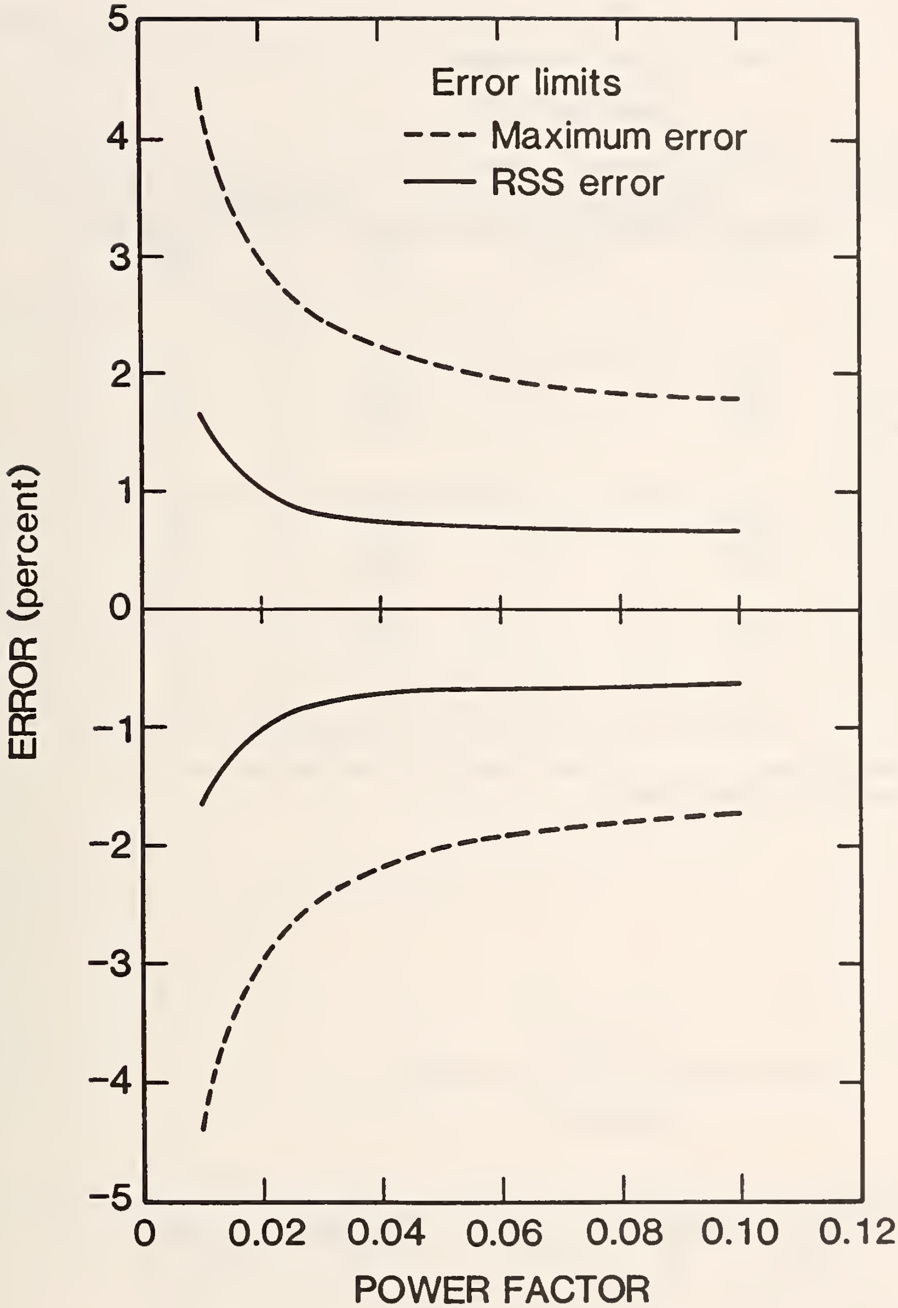


Figure 31. Test System 1, Limits of Errors

Table 17

Errors in Power Measurement

Test System 2

Source of error	RSS error		Maximum error	
	Magnitude (a) (ppm)	Phase angle (b) (μrad)	Magnitude (a) (ppm)	Phase angle (b) (μrad)
Standard				
Current channel	100	13	105	18
Voltage channel	510	14	605	27
Power transducer	2000	50	2000	50
Test System				
Current channel	2000	30	2000	30
Voltage channel	2000	20	2000	20
Power transducer	6500	--*	6500	--*
Current interaction	2000	--	2000	--
TOTAL	7,650	65	15,210	145

*In calibrating the power transducers in the test system, the contributions from magnitude and phase angle errors are combined.

Table 18

Combined Errors in Power Measurement

Test System 2

Power factor cosΘ	RSS error			Maximum error		
	a (%)	b/cos Θ (%)	Total (%)	a (%)	b/cos Θ (%)	Total (%)
0.01	0.765	0.65	1.00	1.52	1.45	2.97
0.02	0.765	0.32	0.83	1.52	0.73	2.25
0.05	0.765	0.13	0.78	1.52	0.29	1.81
0.10	0.765	0.07	0.77	1.52	0.15	1.67
0.20	0.765	0.03	0.77	1.52	0.07	1.59

$$P_t = P_i\ (1 \pm a \pm b/\cos\theta)$$

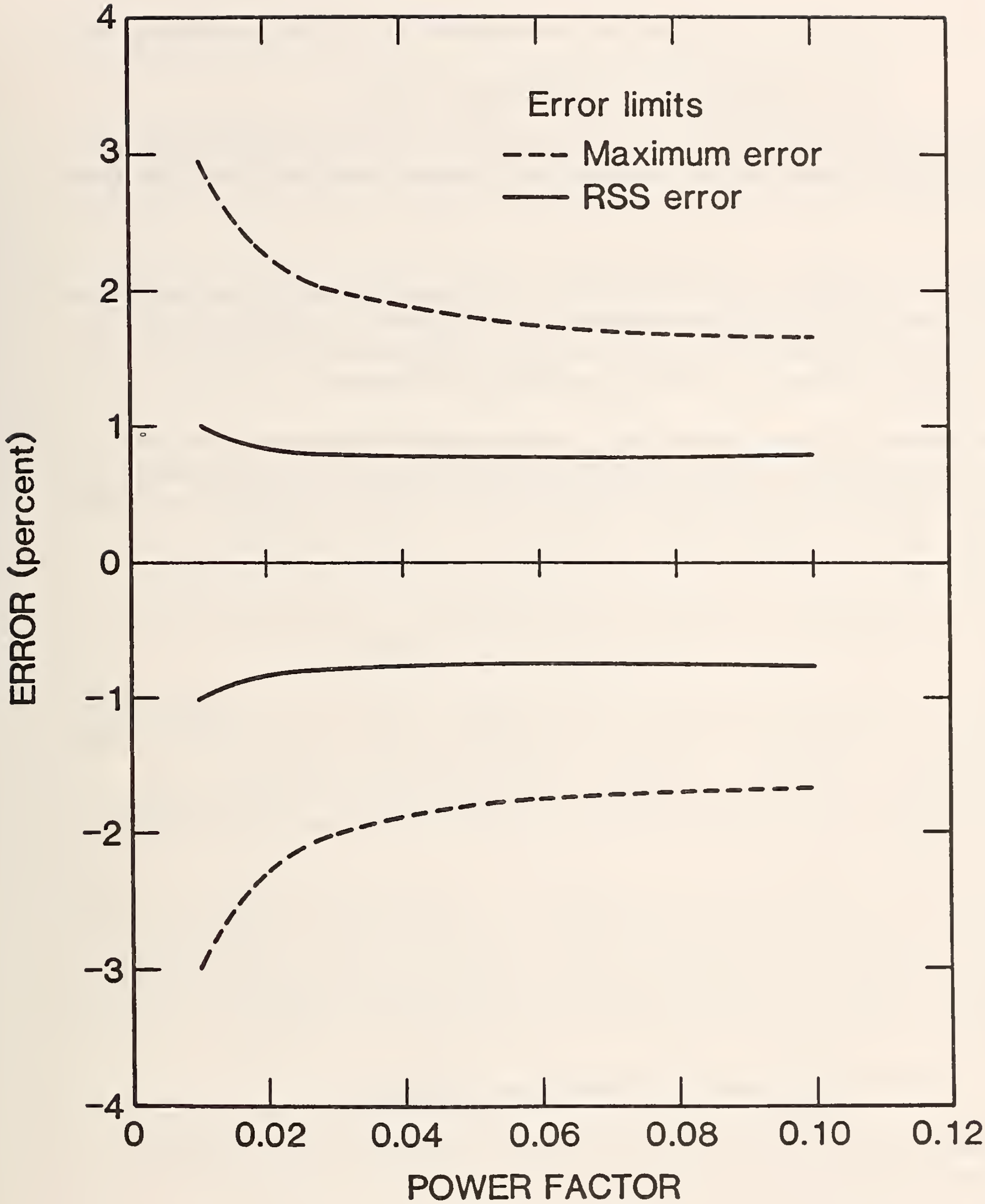


Figure 32. Test System 2, Limits of Errors

9. SYSTEM-BASED VERIFICATION

9.1 Experimental Method and Results

The alignment and calibration of the two test systems is described in section 7. The calibration results for various system components are combined in sections 8.3 and 8.4 to yield the overall measurement error for the test systems.

This approach to verifying the principal components of the test system is highly desirable, as it facilitates diagnosing potential malfunctions in the test system and correcting them. It also reduces the number of possible calibration points and allows an orderly analysis of errors.

Equally desirable, if not essential, is some verification of the test equipment on a system basis, whereby the measurement results of the test system can be compared with those of another, preferably more accurate, system when both measure the same transformer under test. A system based verification may uncover error-producing interactions among the components of the test systems. This step provides an assessment of the severity of electromagnetic interference during the test operation, and verifies whether the methodology of combining the uncertainties is reasonable.

Test system 1 was verified against the standard system on a single-phase basis by measuring simultaneously with both systems, the losses of each phase of a test transformer separately, and then summarizing the results. Verification was done on twenty transformer configurations that cover the principal current and power factor ranges of medium size power transformers manufacturered at ASEA Electric.

The data of the system-based verification is tabulated in Table 19. To illustrate how well the data compare with the estimated errors in section 8.3, the differences in power as measured with the standard and test systems are plotted in Fig. 33. The rss error limits are also plotted, as well as the rss limits corrected for the rss contribution by the standard system.

9.2 Discussion of Experimental Results

Several items from the data in this and the previous two sections are noteworthy and can be summarized as follows:

(1) Both test systems have rss error limits that are ±1% or smaller for power factors of 0.02 and larger.

(2) The system-based tests support a contention that the rss limits are very reasonable for estimating the system accuracy. Of the 20 test points in Fig. 33, 19 are well within the rss limits; one test point is at the limit. The data in Table 19 indicate that the 95% confidence (2σ) limit for the dispersion of the system errors for power measurement is within the estimated rss errors. Also, the dispersion of the errors in current and voltage measurement are within the figures used for estimating the contributions from the current and voltage channels.

(3) The maximum error limits represent, as expected, an overly pessimistic estimate.

(4) The phase angle errors of test system 2 are reduced after alignment to a negligible value, ± 30 μrad maximum. For test system 1, the residual errors are larger, of the order of 100 μrad maximum.

(5) A somewhat surprising result is that the magnitude errors for both test systems are somewhat larger than expected, possibly because the greatest emphasis in alignment and retrofitting was placed on the phase angle error. In future alignments, the causes of magnitude errors will be investigated.

(6) The accuracy goals for the standard system are well exceeded; the current, voltage, and power calibrations meet the present and foreseeable future requirements for medium size power transformers.

Table 19

System-Based Verification
Test System 1

	3 Φ Total power (kW)			3 Φ Average current (A-rms)			3 Φ Average voltage (V-rms)			cos θ	Voltage range (kv)	Current range (A)	
	System 1	Standard	% Error	System 1	Standard	% Error	System 1	Standard	% Error				
1	0.3586	0.3584	+0.06	7.9660	7.9650	+0.01	423.30	423.70	-0.15	0.035	1	10	1
2	0.5685	0.5679	+0.11	10.000	9.9740	+0.26	532.00	531.00	+0.18	0.036	1	10	2
3	5.3660	5.3510	+0.28	200.00	199.90	+0.05	255.30	254.60	+0.27	0.035	1	1000	3
4	12.130	12.091	+0.33	300.00	300.03	-0.01	383.70	382.80	+0.22	0.035	1	1000	4
5	8.4980	8.5590	-0.71	100.00	99.910	+0.09	776.00	774.00	+0.26	0.037	1	1000	5
6	59.460	59.574	-0.19	500.00	499.70	+0.06	765.60	765.10	+0.06	0.052	1	1000	6
7	3.2950	3.2870	+0.24	10.340	10.300	+0.39	1928.0	1927.0	+0.05	0.055	10	10	7
8	3.8450	3.8430	+0.05	25.000	24.970	+0.12	2826.0	2825.0	+0.03	0.018	10	100	8
9	15.430	15.503	-0.47	50.000	49.960	+0.09	5658.3	5651.6	+0.12	0.018	10	100	9
10	44.730	44.820	-0.20	85.000	84.900	+0.12	9617.0	9609.0	+0.08	0.018	10	100	10
11	14.840	14.892	-0.35	50.000	50.000	+0.00	2289.0	2685.0	+0.15	0.037	10	100	11
12	48.180	48.292	-0.23	90.000	89.850	+0.17	4832.0	4824.0	+0.17	0.037	10	100	12
13	3.6680	3.6650	+0.08	20.000	19.990	+0.05	1882.0	1883.0	-0.05	0.032	10	100	13
14	61.370	61.425	-0.09	81.400	81.370	+0.04	7674.0	7669.0	+0.07	0.033	10	100	14
15	9.8320	9.8680	-0.36	20.000	19.990	+0.05	3436.0	3431.0	+0.14	0.048	10	100	15
16	27.720	27.710	+0.04	29.950	29.930	+0.07	5611.0	5607.0	+0.08	0.055	10	100	16
17	57.980	58.103	-0.21	43.010	42.990	+0.05	8058.0	8051.0	+0.09	0.056	10	100	17
18	73.370	73.415	-0.06	48.370	48.330	+0.08	9060.0	9055.0	+0.06	0.056	10	100	18
19	158.40	158.60	-0.13	80.000	79.990	+0.01	13727	13750	-0.17	0.048	100	100	19
20	237.70	237.73	-0.01	98.340	98.070	+0.28	16833	16856	-0.14	0.048	100	100	20
		$\bar{x}$ =	-0.09			+0.10			+0.08				
		s =	0.26			0.10			0.12				
		$\bar{x}$ + 2s =	+0.43			+0.30			+0.32				
		$\bar{x}$ - 2s =	-0.61			-0.10			-0.16				

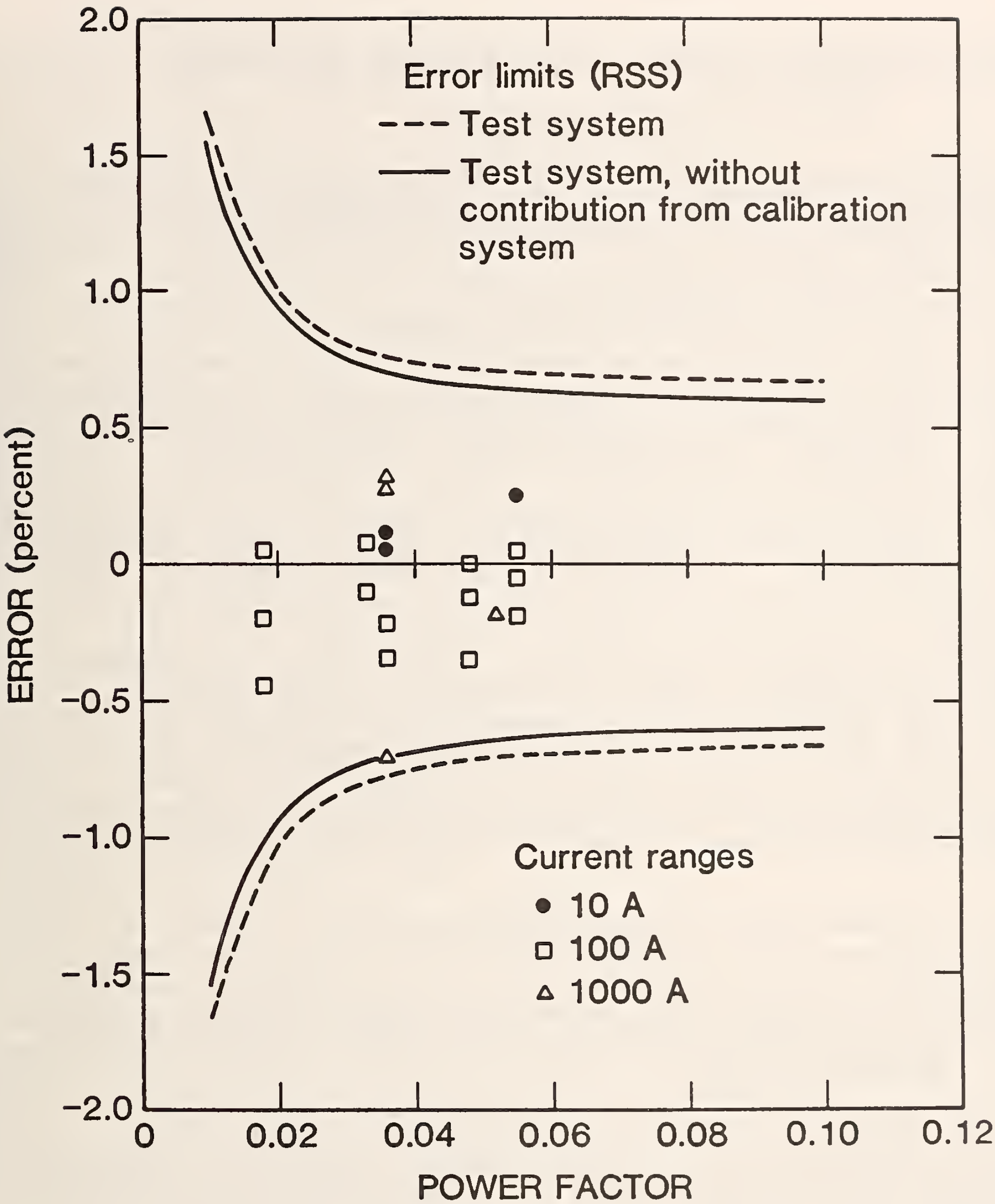


Figure 33. System-Based Verification, Test System 1
Comparison of results as obtained by the test system 1 and standard system

10. MAINTENANCE OF STANDARD INSTRUMENTS AND TEST SYSTEMS

10.1 General Comments

This section provides guidelines for the future calibration of standard instruments and alignment and calibration-related maintenance of test systems. These guidelines are based partly on published information on the stability and failure modes of the devices, as well as on the authors' experiences. The suggested calibration intervals may have to be adjusted as the history of various standard instruments and test systems is accumulated. The fact that drifts in such devices as standard capacitors and resistors are in the magnitude of the quantity, and not in the phase angle, alleviates the calibration problem. In fact, barring significant failures, the phase angle of all standard instruments should remain negligible indefinitely.

The process of calibrating various standard instruments has a number of redundancies. Thus, a failure in an instrument is likely to become apparent in in-house verifications. For example, the ratios and phase angles of both the standard current transformer and the inductive voltage divider should remain unchanged. As the two are compared, a failure in one will become apparent by a relative change between the two. Recordkeeping and convenient presentations of the measurement data are essential in the maintenance of standards. Control charts, and plots of measured data versus time are convenient forms of recordkeeping. It is strongly recommended that the calibration instruments be reserved only for the purpose of performing calibrations and checks in order to minimize the possibility of failures due to accidentally produced excessive voltages and currents and mechanical abuses.

In the use and maintenance of the standard instruments, frequency and harmonic influences have been considered. Most of the standard instruments — current transformers, shunts, standard and high voltage capacitors, standard power transducers — are unaffected by moderate frequency variations up to a few percent. These standard instruments also have adequate harmonic response up to at least the tenth harmonic.

Low voltage capacitive networks used in conjunction with an active divider, and the phase shifter are frequency-sensitive instruments. Effects of their frequency dependence are summarized. In the capacitive network shown in Fig. 21, the effective negative transconductance varies quadratically with frequency. Thus, for a small change in frequency, the change in the compensating transconductance is twice as large. However, this presents no problem if the dissipation factor of the capacitor is small. For example, if the original dissipation factor is 100 ppm, a frequency change of one percent increases or decreases the effective negative transconductance by 2 ppm. Typically, the dissipation factor of these capacitors is relatively independent of frequency. Therefore, the overcompensation or undercompensation is only 1 ppm. In either case, the effect due to small changes in the fundamental frequency is negligible.

In the case of the harmonics, the capacitive network is overcompensated leading to an effective capacitance with negative dissipation factor. However, for lower harmonics — those of interest in tests — the effective dissipation factor levels will not exceed 1000 ppm. Again, the effect on measuring the load losses is negligible, if the harmonic content in the supply is moderate. Only if tests are performed at different fundamental frequency, e.g., 50 Hz, is there a need to change the compensation networks.

In using the active phase shifter of Fig. 25(b) for the calibration of power transducers, the applied power varies as the reciprocal of frequency. Hence, a signal generator having frequency accurate to about ±0.05% is required.

10.2 Standard Current Transformer

As mentioned in section 4.4, in the absence of obvious failures, the current transformer should remain stable indefinitely. Functional verifications, whereby selected ratios of the current transformer are compared against those of the standard inductive voltage divider, and the outputs of the windings of the current transformer are compared, are recommended as in-house checks. Only infrequent calibrations at NBS are needed.

A summary of suggested calibrations and verifications is as follows:

a. Comparison of all ten taps in the secondary winding of the current transformer against the standard inductive voltage divider. Also a similar comparison using the primary and secondary windings to yield 10/1 ratio. Conduct these tests yearly, in-house.

b. Calibration of 1000/1, 100/1, and 10/1 ratios and the corresponding transimpedances with the coaxial shunts. Conduct this calibration every five years, at NBS.

10.3 Standard Shunts

As noted earlier, the phase angle is of primary importance, and since it depends primarily on the geometry of the shunt, the phase angle can be expected to remain stable indefinitely unless the shunt is physically damaged. One of the shunts used by ASEA Electric was calibrated by NBS and its phase angle was found to be negligible. Since the other shunt had identical geometry, its phase angle was also assumed to be negligible. The relative phase angle of both shunts can be monitored in-house by interchanging them in the two-stage current transformer circuit of Fig. 6. Some long-term resistance drifts can be expected, but they should not exceed ten ppm per year and thus should be negligible. Monitoring of the dc resistance is recommended to detect possible accidental abuses.

Here is a summary of suggested calibrations and verifications:

a. DC resistance measurement. Conducted yearly, in-house.

b. Relative phase angle verification using a substitution method. Conducted yearly, in-house.

c. Transimpedance measurement in conjunction with the calibration of the standard current transformer (as in 10.2).

10.4 Standard Capacitors

The standard 1000-pF unit is the primary reference. Its capacitance is expected to remain stable within a few ppm per year. The dissipation factor, assumed to be 5 ppm or smaller, should remain negligible indefinitely. The high voltage capacitor is a completely shielded unit, that is insulated with compressed gas. Two capacitances, 100 pF and 20 pF, are available; only the 100-pF is critical. The dissipation factor is negligible and should remain such. The capacitance value is generally affected by the mechanical rigidity of the device and by the amount of gas in the device. Under normal circumstances, the capacitance should remain stable within 0.01% per year. The solid-dielectric capacitors, 0.01-μF, 0.01 μF, and 1.0-μF units, in the feedback loop of the active divider have a temperature dependence of capacitance of approximately 100-ppm/°C. Long-term drifts of the order of 0.05% per year are possible. The dissipation factor of the solid-dielectric capacitors is in the 60 ppm range. The effective dissipation factor of the transfer capacitance is compensated by the use of the RC type T-networks. It is expected that the dissipation factor of the compensated capacitive network will remain stable within 5 ppm/year. A complete check of all capacitors against the 1000-pF standard is recommended before each major realignment operation. Unexpected changes either in the capacitance value or the dissipation factor could serve as indicators of possible catastrophic failures.

Summary of suggested calibrations and verifications:

a. Relative capacitance and dissipation factor measurements — 1.0-μF, 0.1-μF, 0.01-μF, and 100-pF units against the standard 1000-pF capacitor. Use the bridge of Fig. 23, or, preferably, that of Fig. 24. Conducted yearly, in-house.

b. Calibrate 1000-pF capacitor at NBS. Every two years.

c. Optional — consider acquiring another set of solid-dielectric capacitor networks (1.0 μF, 0.1 μF, and 0.01 μF). Use these for one-to-one comparison with the capacitors in the original set.

10.5 Resistors in the Phase Shifter

The most important factor is the phase angle of the 26,500-ohm resistor. A miniature metal film device is selected having negligible inductance. The effective shunt capacitance is smaller than 0.5 pF, thus, yielding a phase defect of 5 microradians or smaller at 60 Hz. The changes in geometry that would significantly affect the phase angle are gross and thus improbable. Nevertheless acquistions of two input resistors is recommended in order to facilitate checking by a substitution method. The phase angle of the resistors in the feedback path is not important. The knowledge of resistances to $\pm 0.05\%$ of all the resistors is desirable in order to determine the real component of the product of input and output voltages.

Summary of suggested checks and calibrations:

a. Phase angle comparison of two input resistors by a substitution method. Yearly, in-house.

b. DC resistance of all resistors. Yearly, in-house.

10.6 Inductive Voltage Divider

Barring catastrophic failures in transformers or switches, the ratio and phase angle of the inductive voltage divider should remain stable indefinitely. The procedures for checking the standard current transformer described in section 10.2 will also check out the inductive voltage divider.

Additional calibration at NBS is recommended, partially to check the integrity of switches, since some of the failures in switches can produce subtle changes in the ratio of the divider.

Suggested calibration:

a. Ratio and phase angle. Every two years at NBS. As the stability data are accumulated and if they are favorable, the frequency of calibration at NBS can be reduced, e.g., to every five years.

10.7 Standard Power Transducer

The phase shifter is designed to calibrate the power transducer at low power factors. A high accuracy ac voltmeter can be used for calibrations at unity power factor. Since the redundancy in this operation is not as strong as for other calibrations, it is suggested that spot calibrations of the transducer be performed at NBS until evidence is available to demonstrate the reliability of the phase shifter and voltmeter approach.

Suggested calibrations and verification:

a. Calibrate the power transducer using the phase shifter and voltmeter. Conducted yearly, in-house.

b. Perform spot calibrations, e.g., two per range, of the transducer at NBS, every two years.

10.8 Maintenance of Test Systems

In order to ensure test system performance within the error limits established in the earlier sections, periodic alignments and verification on system basis are essential. Design of both systems incorporates built-in low voltage generators (calibrators) that allow for routine verification for proper system operation. These calibrators are signal sources with controlled power factor and controlled signal amplitudes. They feed known low voltage signals into voltage and current buffers. Thus, signal paths beyond primary voltage and current scaling inputs can be readily verified for proper operation. This type of routine functional checking assures that no major drifts or misalignments have taken place. These checks, however, do not provide traceable calibration of the total measurement system.

Experience gained over the years on the operation and stability of both test systems indicate that these internal generators do not produce calibration signals that are of adequate phase stability. The amplitude stability, however, is quite good. Hence, the use of a built-in generator should only be made to provide gross assurance of systems performance. Use of the signals from calibrators for the alignment of current and voltage buffers is not desirable.

Based on ASEA Electric's experience, this gross system check by use of built in generators should be done once a month. This check should be used to provide evidence of system operation without major malfunctions. Data derived from such checks can show trends in drifts and signal degradation. Such checks can also be used as trouble shooting aids in localizing faults in test systems. Over the years, such generators have identified faulty operational amplifiers, rms transducers, and unstable power transducers. Alignment of current channels, voltage channels, power transducers, as well as system-based verification utilizing procedures described in previous sections or equivalent procedures are required to obtain calibration data that can be defined as being traceable.

As discussed earlier, both systems were modified at ASEA Electric to provide noninteracting adjustments in both the voltage and current channels. Modifications in circuit designs were also necessary to limit the effect of drifts in circuit components. In order to ensure that these modifications yielded desired performance, current, voltage and power channel alignments were checked three times within the past year using the procedure outlined earlier. Results of these checks indicate that implemented modifications were necessary to control and eliminate component drifts. System alignments did not change significantly. Due to the critical nature of measurements and their significant economic impact, it is felt that traceable system-based verification and alignments of the subsystems be carried out at least once every year.

The necessity for a yearly alignment is based on the following considerations:

a. Although standard gas capacitors are extremely stable devices, gas pressure changes due to leaks or loading, vibrations, or ambient environmental changes can introduce a variation in active capacitance that may have a significant impact on measurement accuracies.

b. Precision current transformers should provide stable long-term performance. However, subtle failures of transformers and their burdens are possible and could introduce measurement errors.

c. Electronic components do drift and age. Their performance may slowly change over a period of time. In addition, the effect of factory environment and electrical noise levels may create conditions that can adversely affect the system performance.

A long-term, (e.g., five-year) study of trends in the stability of subsystems alignment should be made before system-based verification and alignment requirements can be relaxed.

11. DISCUSSION AND CONCLUSIONS

Discussion

The authors hope that some of the technical ideas, calibration hardware, measurement procedures, and methodology for evaluation of system errors described in this report will help lead to an industry-wide consensus standard dealing with the requirements of accuracy and traceability in measurement of transformer losses. By this, or an equivalent procedure, a uniform comparison of losses in power transformers could be made. A complete statement of measurement accuracy for a loss test system requires that the measurement uncertainties of the system be shown through a calibration process that is traceable.

In order to develop a diverse data base related to transformer loss measurement uncertainties, a "round-robin" comparison of measurement results on the same transformer would be necessary. Such a comparison would provide an excellent indication of the state of overall measurement capability within the industry.

Although the calibration (standard) system described in this report was specifically tailored to calibrate two test systems at ASEA Electric, the concepts and many of the developments presented in this report are broadly applicable for the calibration of all types of test systems shown in Fig. 1. With relatively simple modifications, test systems that utilize bridge techniques for loss measurements can be calibrated also.

To achieve high accuracies in the two test systems at ASEA Electric, considerable effort and care were expended in retrofitting and modifying the principle components. In the authors' judgment, this work should be performed by a skilled technician under the guidance of a knowledgeable engineer. This will ensure that future maintenance and alignment of the test system, as well as on-line equipment calibrations would be carried out by an experienced and qualified personnel.

Conclusions

The following conclusions summarize the developments reported in this technical note:

(1) The calibration (standard) system described in this document provides a means to achieve traceable measurements of transformer losses. This system is utilized not only to perform calibration and alignment of principle components in a test system, but also is designed to provide a system-based verification for the entire loss test system.

(2) Methodology for combining errors in principal components to arrive at an estimate of total test system error at various power factors is presented. System-based verification tests demonstrated the validity and adequacy of this approach.

(3) The self-contained calibration plan detailed in his report provides a simple means to achieve traceability. This approach requires sending only a few small instruments for infrequent calibration to outside organizations such as NBS.

(4) The necessary steps for improving measurement accuracy and for establishing traceability are detailed in Appendix 2. It is estimated that the cost of such actions may be only a fraction of the cost of losses in a single medium-size power transformer.

(5) Suggestions are made regarding accuracy goals for loss test systems of the future. Specifics are presented in Appendix 2.

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13. APPENDIX 1 -- CALIBRATION REPORTS AND DATA

13.1 Introductory Comments

Calibration or test reports for six standard instruments are included in this technical note. These reports are, for the most part, self explanatory. However, several comments are in order. Report 13.4 on the 1000-pF standard capacitor does not contain information on the dissipation factor since the dissipation factor values are not provided with this calibration service. Comparisons of high quality gas-dielectric capacitors indicate that the dissipation factors do not differ among units by two or three parts per million, Hence, it is assumed that the absolute value is within 5 ppm.

Report 13.6 on the inductive divider gives large estimated calibration uncertainty for the quadrature component — $\pm 5 \times 10^{-6}$ of the input quantity. At small ratios the uncertainty becomes quite large, e.g., $\pm 50 \times 10^{-6}$ at the ratio of 0.1. The inductive divider was compared against the two-stage transformer using the circuit of Fig. 14(a). The results are reported in section 13.6, Table 20. Combining on rss basis the largest phase angles of ratio (b/A) in Tables 3 and 20 with the measurement uncertainty in Table 20, yields ± 6.0 μrad. It is impractical to apply phase angle correction to the inductive divider. The residual corrections are treated as errors. On basis of the above data an allowance of ± 10 μrad is made for possible phase angle errors of inductive divider.

13.2 Two-Stage Current Transformer

FORM NBS-259
(REV. 12-78)

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

REPORT OF TEST

TWO-STAGE CURRENT TRANSFORMER
10-1000 to 1 Ampere, 60 Hertz

Submitted by
ASEA Electric Inc.
400 South Prairie Avenue
Waukesha, Wisconsin 53186

Frequency (hertz)	Secondary Burden	Secondary Current (amperes)	Current Ratio	Phase Angle (microradians)
60	A	1.0	10 x 1.000000	-4
		0.5	1.000000	-4
		0.2	1.000000	-3
		0.1	0.999999	-2
	B	1.0	1.000000	-1
		0.5	1.000000	0
		0.1	0.999998	+3
	A	1.0	100 x 0.999997	-3
		0.5	0.999997	-3
		0.2	0.999997	-3
		0.1	0.999997	-4
	B	1.0	0.999997	0
		0.5	0.999997	0
		0.1	0.999997	-1
	A	1.0	1000 x 1.000000	-2
		0.5	1.000000	-2
		0.2	0.999999	-2
		0.1	1.000000	-2
	B	1.0	1.000000	+1
		0.5	1.000001	+1
		0.1	1.000000	+2

Date of Test: June 27, 1984

722/233345-84

Secondary burden A consisted of separate resistances of 2 ohms each in both the secondary and tertiary circuits. Secondary burden B consisted of resistances less than 0.1 ohm each in both the secondary and tertiary circuits.

It is very unlikely that the above values of current ratio and phase angle are in error by more than 10 ppm and 10 microradians, respectively. These figures include allowances for both the random and systematic errors of the calibration process.

For the Director
National Engineering Laboratory

Barry A. Bell

Barry A. Bell, Group Leader
Electronic Instrumentation and Metrology
Electrosystems Division

Test No: 722/233345-84
Order No: 76625
Date: August 8, 1984

13.3 Two-Stage Current Transformer/Shunt Combination

FORM NBS—259
(REV. 12-78)

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

REPORT OF TEST

TWO-STAGE CURRENT TRANSFORMER/AC SHUNT COMBINATION
ASEA Transformer, 10-1000 to 1 Ampere, 60 Hertz

Submitted by
ASEA Electric Inc.
400 South Prairie Avenue
Waukesha, Wisconsin 53186

The transfer resistance and phase angle of this transformer-shunt combination were measured in June, 1984, with the shunt having serial no. 6829 connected across the transformer's secondary winding, and the remaining shunt, serial no. 6828, connected across the tertiary winding. The measured values and test conditions are reported below.

Room Temperature	Frequency (hertz)	Transformer Ratio	Primary Test Current (amperes)	Resistance (ohms)	Phase Angle (microradians)
24°C	65	100/1	20	0.01999302	-2.6
	65	1000/1	40	0.00199930	-1.8

It is unlikely that the above values of resistance and phase angle are in error by more than 0.01 percent and 5 microradians, respectively.

For the Director
National Engineering Laboratory

Barry A. Bell

Barry A. Bell, Group Leader
Electronic Instrumentation and Metrology
Electrosystems Division

Test No: 722/233345-84
Order No: 76625
Date: August 8, 1984

13.4 Standard Capacitor

U. S. Department of Commerce
NATIONAL BUREAU OF STANDARDS
National Measurement Laboratory
Washington, D.C. 20234

REPORT OF CALIBRATION

Description of Standard:
Standard Capacitor

Submitted By:
RTE-ASEA
Waukesha, WI 53186
P.O. No. 60794

Temperature: 23 Degrees Celsius
Date of Calibration: 1 March 1984

FREQUENCY (Hertz)	CAPACITANCE (Picofarads)	LIMITS OF UNCERTAINTY s	Total
100	999.95	8 ppm	25 ppm

For additional information regarding the calibration of standard capacitors the user should consult the information sheet(s) enclosed with this report.

For The Director
National Measurement Laboratory

Norman B. Belecki, Physicist
Center For Basic Standards
Electricity Division

Test No. 232213
Date: 1 March 1984

FORM NBS-443
(REV. 11-65)

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

REPORT OF CALIBRATION

CAPACITORS
0.01, 0.1, and 1 Microfarad

Submitted by

ASEA Electric Inc.
400 South Prairie Avenue
Waukesha, Wisconsin 53186

The capacitance and dissipation factor of the three capacitors were measured on June 27, 1984, at a frequency of 60 Hz and a room temperature of 21.5°C. The results are tabulated below.

Voltage (volts)	Capacitance (farads)	Dissipation Factor
0.01 Microfarad Nominal Standard		
10	1.000332×10^{-8}	$+6 \times 10^{-6}$
dissipation factor adjusted to zero		
10	1.000346×10^{-8}	0×10^{-6}
20	1.000358	0
35	1.000383	0
5	1.000345	0
0.1 Microfarad Nominal Standard		
10	1.001018×10^{-7}	-13×10^{-6}
dissipation factor adjusted to zero		
10	1.001020×10^{-7}	0×10^{-6}
20	1.001021	0
35	1.001027	0
5	1.001022	0
1 Microfarad Nominal Standard		
10	0.999786×10^{-6}	0×10^{-6}
20	0.999786	0
35	0.999792	+1
5	0.999788	0

722/233345-84

CAPACITORS
0.01, 0.1, and 1 microfarad
ASEA Electric Inc.

<u>Estimated Uncertainties</u>
Capacitance: ±0.003% of measured value
Dissipation Factor: $\pm 5 \times 10^{-6}$
Temperature: ±1°C

For the Director
National Engineering Laboratory

for Robert E. Hebner, Group Leader
Applied Electrical Measurements
Electrosystems Division

Test No: 722/233345-84
Order No: 76625
Date: August 7, 1984

13.6 Inductive Divider

U. S. Department of Commerce
NATIONAL BUREAU OF STANDARDS
National Measurement Laboratory
Washington, D. C. 20234

REPORT OF CALIBRATION

Description of Standard:

Submitted By:
RTE/ASEA Corporation
Waukesha, WI 53186
P.O. No. 60794

Date of Calibration: 10 February 1984

Temperature: 23 Degrees Celsius

Input Voltage Distortion: Negligible

Output Burden: Negligible

Case connected to input low terminal (COMMON)

The in-phase and quadrature corrections for each dial setting given below are the four-terminal transfer ratio corrections. Any dials not given in the dial setting were set to zero. To obtain the actual transfer ratio for a dial setting, the corrections must be multiplied by 10 exp-6 and then added as the appropriate complex components to the nominal value of the dial setting.

The standard deviations given below are those for an individual measurement of the corrections. To relate these to the actual transfer ratios, they must be multiplied by 10 exp-6. The uncertainty will be increased if the magnitude of the standard deviation of any individual step is sufficiently large.

For further information regarding the use of the calibration results and the calibration of this standard, the user should consult the information sheet(s) enclosed with this report.

Test No. 232213

Frequency 100 Hertz; Input Voltage: 25 Volts

	CORRECTIONS		STANDARD DEVIATION		NUMBER
DIAL SETTING	IN-PHASE	QUADRATURE	IN-PHASE	QUADRATURE	MEASUREMENTS
X	0.00	0.0	0.000	0.00	3
.9	0.28	-1.5	0.000	0.00	3
.8	0.25	-1.6	0.000	0.00	3
.7	0.22	-1.4	0.000	0.00	3
.6	0.19	-1.1	0.000	0.00	3
.5	0.13	-0.7	0.000	0.00	3
.4	0.11	-0.3	0.000	0.00	3
.3	0.09	0.1	0.000	0.00	3
.2	0.04	0.3	0.000	0.00	3
.1	0.03	0.3	0.000	0.00	3
0	0.02	0.0	0.000	0.00	3
0X	-0.27	1.4	0.000	0.00	3
09	-0.22	1.1	0.000	0.00	3
08	-0.19	0.9	0.000	0.00	3
.07	-0.16	0.8	0.000	0.00	3
.06	-0.13	0.7	0.000	0.00	3
.05	-0.11	0.6	0.000	0.00	3
.04	-0.08	0.5	0.000	0.00	3
.03	-0.05	0.4	0.000	0.00	3
02	-0.03	0.3	0.000	0.00	3
.01	0.00	0.2	0.000	0.00	3
.00X	-0.05	0.3	0.000	0.00	3
.009	-0.04	0.2	0.000	0.00	3
008	-0.04	0.2	0.000	0.00	3
007	-0.03	0.2	0.000	0.00	3
.006	-0.02	0.2	0.000	0.00	3
.005	-0.01	0.1	0.000	0.00	3
.004	-0.01	0.1	0.000	0.00	3
.003	0.00	0.1	0.000	0.00	3
.002	0.01	0.1	0.000	0.00	3
.001	0.02	0.0	0.000	0.00	3
000X	0.01	0.2	0.000	0.00	3
699X	-0.07	-0.2	0.000	0.00	3
299X	-0.20	1.4	0.000	0.00	3

The limits of uncertainty for the corrections above are estimated to be 0.5 x 10 exp-6 for the in-phase corrections and 5. x 10 exp-6 for the quadrature corrections.

For The Director
National Measurement Laboratory

Norman B. Belecki, Physicist
Center For Basic Standards
Electricity Division

Test No 232213
Date 10 February 1984

GENERAL INFORMATION ON STANDARD DECADE TRANSFORMER DIVIDERS

Standard decade transformer dividers are calibrated by comparison with NBS reference standards. The correction given in the calibration reports are in terms of the four-terminal transfer ratio at the terminals of the divider. In the following, the definitions and nomenclature follow the American National Standard for decade transformer dividers (voltage type), ANSI C100.1 - 1972.

The transfer ratio of a decade transformer divider is defined as

$$E_o/E_i = A_n + a + jb$$

where

E_o = output voltage

E_i = input voltage

A_n = nominal transfer ratio (dial setting of the divider)

a = transfer ratio in-phase correction times 10^{-6}

b = transfer ratio quadrature correction times 10^{-6}

As indicated above, the corrections given in the calibration report must be multiplied by 10^{-6} before use in the equations.

If in actual use the input terminals are defined at the ends of connecting leads, the voltage drop across these leads enters into the ratio corrections in the following way.

$$E_o/E_i' = (A_n + a + jb)/(1 + Z_1/Z_2)$$

where

$E_i' - E_i$ = voltage across input leads

Z_1 = impedance of input leads

Z_2 = input impedance of the divider

The transfer ratio angle correction is defined as

$$\theta = \tan^{-1} [b/(A_n + a)]$$

where

θ = transfer ratio angle correction (in radians)

The transfer ratio angle correction is included here because the previous calibration may contain the quadrature component as a phase angle which is the same as the transfer ratio angle correction. A useful approximation to the above equation is

$$\theta = b/A_n$$

Table 20

Comparison of Inductive Divider against Two-Stage Transformer

Tap of two-stage transformer (A)	Quadrature correction of IVD relative to two-stage transformer (b, absolute value)
0.1	0.30×10^{-6}
0.2	0.56
0.3	0.69
0.4	0.84
0.5	0.85
0.6	0.78
0.7	0.70
0.8	0.64
0.9	0.36
1.0	3.00

$-I_2/I_1 = V_1/V_2 = A + a + jb$

where A is the nominal ratio,
a is the in phase correction
b is the quadrature correction
phase angle of ratio $\approx b/A$ radians.

Estimated uncertainty in measurement of $b = 5A \times 10^{-6}$.

13.7 Power Transducer

FORM NBS—259
(REV. 12-78)

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

REPORT OF TEST

WATT CONVERTER
1.25, 2.5, 5 Volts, 0.01, 0.1, 1.0 Power Factors

Submitted by

ASEA Electric Inc.
400 South Prairie Avenue
Waukesha, Wisconsin 53186

The watt converter was tested as a voltage multiplier at 60 Hz with nearly sinusoidal waveforms. The test was performed in June 1984 at a room temperature of approximately 23°C.

Measurements were made after a warm-up period of at least one hour by applying voltages of known rms value and phase angle to the converter inputs V1 and V2. The power factor switch was adjusted to give maximum resolution and the reading on the converter digital display was recorded. The voltage waveforms were digitally synthesized by the NBS Phase Angle Standard and measured by a calibrated rms responding voltmeter.

To minimize interactions between the power line and the synthesized test signal, all of the instrumentation was powered from a 70-Hz supply.

The converter reading was adjusted to zero with V1 and V2 disconnected, however readings as large as 0.35 percent were observed with rated voltage applied to V2; and with V1 disconnected.

Test results are shown in Tables I and II where the watt converter errors are computed in terms of full scale range by the following relationship:

$$\text{Percentage error} = \frac{\text{reading} - (\text{V1 x V2 x power factor}) \text{ applied}}{(\text{V1 x V2 x power factor}) \text{ range}} \times 100$$

At lagging power factor, the voltage applied at V2 lags the voltage applied at V1.

The estimated uncertainty in the product of the applied voltage (V1 and V2) is 0.2 percent. The power factor is given by cos $(\theta \pm \phi)$ where θ is the nominal phase angle between V1 and V2 and ϕ is the estimated uncertaninty in this angle ($\phi = 50 \times 10^{-6}$ radians for the values in Table I and $\phi = 100 \times 10^{-6}$ radians for the values in Table II). The lower uncertainity assigned to the values in Table I is due to the measurement procedure which allowed the exchange of the signals applied to V1 and V2 without amplitude adjustment.

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To increase resolution, some of the measurements (from Table I) were made on a power factor range which was lower than the actual applied power factor. For example on the 5-volt range with 2 volts applied at 0.1 power factor, readings were taken on the 0.01 power factor switch position. The errors, however, are reported in terms of the 0.1 power factor range (corrresponding to the actual power factor). Measurements at zero power factor were made on the 0.01 power factor range and results are reported in terms of the 0.01 power factor range.

For the Director
National Engineering Laboratory

Barry A. Bell

Barry A. Bell, Group Leader
Electronic Instrumentation and Metrology
Electrosystems Division

Test No: 722/233345-84
Order No: 76625
Date: August 7, 1984

Table I

Watt Converter Errors in Percent of Full Scale Range

Voltage Range (volts)		Applied Volts (nominal)		Power Factor								
				0.00		0.01		0.1		0.5		1.0
V1	V2	V1	V2	lead	lag	lead	lag	lead	lag	lead	lag	
5	5	5	5	0.0	+1.1	-0.9	+0.2	-0.7	-0.6	0.0	0.0	0.0
5	5	4	4	0.0	+0.7	-0.6	+0.2	-0.4	-0.4	0.0	0.0	0.0
5	5	3	3	-0.1	+0.4	-0.4	0.0	-0.3	-0.2	-0.10	-0.10	0.0
5	5	2	2	-0.1	+0.1	-0.2	-0.1	-0.14	-0.13	-0.05	-0.04	-0.09
5	5	1	1	0.0	0.0	-0.1	0.0	-0.04	-0.03	-0.01	-0.01	-0.02
2.5	2.5	2.5	2.5	+0.9	+0.3	0.0	-0.6	-0.6	-0.7	0.0	0.0	0.0
1.25	1.25	1.25	1.25	+0.3	+0.6	-0.6	-0.2	-0.7	-0.6	0.0	0.0	0.0

Errors with 0.01 percent resolution indicate measurements were made on a power factor range lower than the applied power factor.

Table II

Watt Converter Errors in Percent of Full Scale Range

Voltage Range (volts)		Applied Volts (nominal)		Power Factor								
				0.00		0.01		0.1		0.5		1.0
V1	V2	V1	V2	lead	lag	lead	lag	lead	lag	lead	lag	
5	2.5	5	2.5	-0.1	+0.7	-0.7	-0.2	-0.7	-0.6	0.0	0.0	0.0
2.5	5	2.5	5	+0.3	+0.3	-0.3	-0.6	-0.6	-0.7	0.0	0.0	0.0
5	1.25	5	1.25	-0.2	+0.4	-0.8	-0.4	-0.7	-0.6	0.0	0.0	0.0
1.25	5	1.25	5	-0.4	+0.8	-1.0	0.0	-0.7	-0.6	0.0	0.0	0.0
2.5	1.25	2.5	1.25	+0.5	-0.1	-0.1	-1.0	-0.6	-0.7	0.0	0.0	0.0
1.25	2.5	1.25	2.5	+0.1	+0.4	-0.5	-0.5	-0.6	-0.6	0.0	0.0	0.0

722/233345-84

14. APPENDIX 2 — SUGGESTED CALIBRATION PROCEDURE AND ACCURACY GOAL

14.1 Calibration Procedure

Recommended specific steps for achieving an accurate and "traceable" test system are summarized below:

(a) Analyze the existing test system for magnitude and phase errors in principal components — current and voltage transformers, power transducers, voltage dividers, etc.

(b) Evaluate the existing test environment in terms of the influences of electromagnetic fields and electrical noise; shielding and grounding practices.

(c) Determine the power source waveform purity (harmonic content), frequency stability, and magnitude stability.

(d) Evaluate system errors at various load loss power factors based on data obtained in (a), (b), and (c) utilizing technically sound methodology. (Examples of methodology are presented in this report).

(e) Establish goals for accuracy and traceability requirements for the principal components of and for the whole test system.

(f) Construct or acquire calibration (standard) system components such as those described in this report or equivalent. Determine their accuracy.

(g) Align principal components in the test system to satisfy the requirements established in (e). If necessary, modify and retrofit the test system.

(h) Document the residual errors (magnitude and phase) in each of the principal components of the test system.

(i) Combine the residual errors of the test system with those of the calibration system, and thus determine the total test system error at various power factors. A methodology for combining errors is outlined in this report.

(j) Conduct system-based verificaton by comparing the results obtained with the test and standard systems.

(k) Compare the results obtained in (j) against those in (i). If significant discrepancies are found, investigate and correct the causes of these discrepancies.

(l) In general, strive for independent methods to verify the accuracy of the measurements.

(m) Finally, implement a continuing calibration or Measurement Assurance Program, such as the one recommended in this report, to ensure that the traceability requirements in (e) are met for the critical standard instruments and the test system.

14.2 Accuracy Goal

In view of the instrumentation and measurement technology that is available, the authors suggest the accuracy goals listed in Table 21 as challenging but achievable in future test systems where power losses have to be measured at power factors of 0.01 and larger. In actual use of such a test system, some degradation in performance may occur due to instabilities that are not caused by the test system itself. Hence, a safety factor of perhaps 2 may have to be applied to the numbers in Table 21 to arrive at realistic, achievable measurement accuracies.

Table 21

Suggested Goal for Limits of Errors of Future Test Systems

(a) Errors in principal components

Source of error	Error	
	Magnitude (%)	Phase Angle (μrad)
Current channel	0.1	50
Voltage channel	0.1	50
Power transducer	0.2	50
Current measurement interaction	0.2	--
RSS	0.32	87

(b) Combined error

Power Factor	Error in power measurement (%)
0.01	0.93
0.02	0.54
0.05	0.36
0.10	0.33

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO.	2. Performing Organ. Report No.	3. Publication Date
	NBS/TN-1204		September 1985

4. TITLE AND SUBTITLE

CALIBRATION OF TEST SYSTEMS FOR MEASURING POWER LOSSES OF TRANSFORMERS

5. AUTHOR(S)

Oskars Petersons and S. P. Mehta

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

National Bureau of Standards
U.S. Department of Commerce
Gaithersburg, MD 20899

7. Contract/Grant No.

8. Type of Report & Period Covered

Final

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

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)

A calibration system for accuracy verification and alignment of test systems for measuring transformer losses is described. Methodologies are presented for assessing measurement uncertainties and for evaluating overall accuracy of test systems. Procedures are suggested for continuing maintenance and calibration of standard instruments and test systems to ensure traceable measurements.

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

calibration; loss measurement; low power factor; power transformers; traceability

13. AVAILABILITY

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