INSTRUCTION MANUAL

MODEL 258

VOLT-AMPERE-WATT METER

(Serial Nos. greater than 92,000)

(212) 255-2940

clarke·hess

COMMUNICATION RESEARCH CORP.

220 W. 19th STREET • NEW YORK, N.Y. 10011

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MODEL 258 V-A-W METER
TRUE RMS, WAVESHAPE INDEPENDENT CURRENT, VOLTAGE AND POWER MEASUREMENTS
50 Hz to above 1000 kHz

COMPLETE IEEE-488 PROGRAMING as a SELF CONTAINED OPTION

While the Model 258 may be equipped with a large assortment of input VOLTAGE and/or CURRENT ranges. The standard version is supplied with the following ranges.

VOLTAGE RANGES

FULL SCALE VOLTAGE	CALIBRATED RANGE	NORMAL RESOLUTION	EXPANDED RESOLUTION
20.00 V	2.00 - 40.00 V	10 mV	4 mV
100.0 V	10.0 - 200.0 V	100 mV	20 mV
200.0 V	20.0 - 400.0 V	100 mV	40 mV

CURRENT RANGES

FULL SCALE CURRENT	CALIBRATED RANGE	NORMAL RESOLUTION	EXPANDED RESOLUTION
50.00 mA	5.00 - 100.00mA	10 uA	10 uA
250.0 mA	25.0 - 500.0 mA	100 uA	50 uA
500.0 mA	50.0 - 1000 mA	100 uA	100 uA
2500 mA	250 - 5000 mA	1 mA	500 uA

POWER AND POWER X 10 RANGES

There are TWELVE Full Scale POWER ranges and TWELVE Full Scale POWER X 10 ranges. For the indicated VOLTAGE and CURRENT ranges the Full Scale values for POWER vary from 1.000 W to 500.0 W while for POWER X 10 they vary from 100.0 mW to 50.00 W. The "5000 digit expansion feature" will allow the Full Scale value of any range to be set to 5000 digits. This means that with expanded resolution on the 1.000 W range the available resolution is 0.2 mW while on the 100.0 mW range the expanded resolution is 20 uW.

VOLTAGE and CURRENT ACCURACY

All voltage ranges and all current ranges have identical frequency responses.

Accuracy : ±0.5% Rdg ± 0.5% Range 50 Hz to 1000 kHz.
±0.5% Rdg ± 1.0% Range 1000 kHz to 1500 kHz.

POWER or POWER X 10 ACCURACY for LOADS of ANY Power Factor.

50 Hz to 1000 kHz
Accuracy : ±0.75% of input Volt-Ampere product ±0.75% of range

WARRANTY

All CLARKE-HESS instruments are warranted against defects in materials and workmanship. This warranty applies for one year from the date of delivery of the instruments. The CLARKE-HESS Communication Research Corp. will repair or replace instruments that prove to be defective during the warranty period. For such repair or replacement, the instrument must be returned to us (See Section 5-0 for details) and must, in our opinion, not have been subjected to unreasonable usage or internal reworking. No other warranty is expressed or implied.

CLARKE-HESS assumes no liability for secondary charges or for consequential damages.

ABBREVIATIONS AND CONDENSATIONS USED IN THIS MANUAL

AC	Alternating Current
C	Capacitor
COM	Common
CR	Crystal Rectifier - Diode
D	Diode
DC	Direct Current
FS	Full Scale
(ftf)	(from the front)
HFC	High Frequency Clock
I	Current
IC	Integrated Circuit
LED	Light Emitting Diode
LFC	Low Frequency Clock
LL	Load Latch Pulse
NGT	Negative Going Transition
NP	Negative Polarity Pulse
PF	Power Factor
PGT	Positive Going Transition
PP	Positive Polarity Pulse
PROM	Programable Read Only Memory
Q	Transistor or Latch Output Signal
R	Resistor
S	Switch
V	Voltage
VA	Volt Amperes

DESCRIPTION

The Model 258 is an AC coupled, broadband, waveshape independent and power factor independent, true RMS reading instrument. It has the same high accuracy for true average POWER readings from 50 Hz to 1000 kHz and the same high CURRENT and VOLTAGE accuracy from 50 Hz to 1000 kHz. Since the instrument is RMS reading all VOLTAGE and CURRENT readings are positive. POWER or POWER X 10 readings may be either positive or negative depending upon the circuit connections and upon the direction of current flow through the input CURRENT transformer.

The POWER X 10 position offers ten times the resolution of the POWER position. It may be employed when both the CURRENT and the VOLTAGE inputs are 40% or less of FULL SCALE. (30% with crest factors greater than four.)

As pointed out under "Wide Measurement Range" the Model 258 may be equipped with a large assortment of input VOLTAGE and/or CURRENT ranges. The standard version is supplied with the following ranges.

VOLTAGE RANGES

FULL SCALE VOLTAGE	CALIBRATED RANGE	NORMAL RESOLUTION	EXPANDED RESOLUTION
20.00 V	2.00 - 40.00 V	10 mV	4 mV
100.0 V	10.0 - 200.0 V	100 mV	20 mV
200.0 V	20.0 - 400.0 V	100 mV	40 mV

CURRENT RANGES

FULL SCALE CURRENT	CALIBRATED RANGE	NORMAL RESOLUTION	EXPANDED RESOLUTION
50.00 mA	5.00 - 100.00 mA	10 uA	10 uA
250.0 mA	25.0 - 500.0 mA	100 uA	50 uA
500.0 mA	50.0 - 1000 mA	100 uA	100 uA
2500 mA	250 - 5000 mA	1 mA	500 uA

POWER AND POWER X 10 RANGES

There are TWELVE Full Scale POWER ranges and TWELVE Full Scale POWER X 10 ranges. For the indicated VOLTAGE and CURRENT ranges the Full Scale values for POWER vary from 1.000 W to 500.0 W while for POWER X 10 they vary from 100.0 mW to 50.00 W. The "5000 digit expansion feature" will allow the Full Scale value of any range to be set to 5000 digits. This means that with expanded resolution on the 1.000 W range the available resolution is 0.2 mW while on the 100.0 mW range the expanded resolution is 20 uW.

ACCURACY and INPUT IMPEDANCE VOLTAGE CHANNEL

Input Impedance: 1 Megohm and 7 pF.
All voltage ranges have identical frequency responses.
RMS values between one tenth and twice the nominal Full Scale Value

Accuracy: ±0.5% Rdg ±0.5% Range 50 Hz to 1000 kHz.
±0.5% Rdg ±1.0% Range 1000 kHz to 1500 kHz.

ACCURACY and REFLECTED IMPEDANCE CURRENT CHANNEL

Input is via two broadband CURRENT transformer inputs. With the CT-411 transformer the reflected impedance is 0.2 milliohm for the ranges of 500.0 mA or higher. The reflected impedance increases for lower current ranges. With the CT411 transformer full scale ranges below 500.0 mA require multiple primary turns on the current transformer. Since the reflected impedance increases with the square of the turns ratio the reflected impedance with the 10 turns required for a full scale sensitivity of 50.00 mA is 100 times the 0.2 milliohms from a single turn or 20 milliohms.

Accuracy: Same as in the voltage case

POWER or POWER X 10 ACCURACY for LOADS of ANY Power Factor

Accuracy: ±0.75% of input VA ±0.75% of range.
50 Hz to 1000 kHz

The -3 dB frequency for the CT-411 transformer is about 1 Hz therefore the CURRENT transformer will contribute about +0.6 degrees of current channel phase shift at 100 Hz. Less than 0.06 degrees of phase shift will result from the transformer above 1000 Hz. A 0.168 uF series coupling capacitor is included in the input attenuator of the voltage channel to cause a 1 Hz breakpoint in the voltage channel also. This "phase matching" of the two channels allows reasonable low power factor power measurements to be made down to 50 Hz.

CREST FACTOR

(Ratio of peak input to Full Scale RMS value of the range.)

Greater than FOUR for all ranges and functions. (The highest VOLTAGE range may be further restricted by either dynamic range limits or an absolute peak limit of 900V.) Typical "excess peak error" is 0.1% for a Full Scale RMS pulsed waveshape having a crest factor of SIX.

DISPLAY

The Model 258 has a full four digit display made up of 10.9 mm (0.43 inch) high LED units mounted in sockets on a separate display board. A non-glare optical filter covers the display. Decimal point and full scale switching with functions and/or ranges is automatic. Four separate light emitting diodes indicate NEGATIVE power, OVERLOAD, MILLIWATTS, and F.S. = 5000. The display board is interchangeable WITHOUT changing the calibration status of the instrument. By using the leading zero suppression in conjunction with the "overload" lamp, the full scale equals 5000 digit position, and the twice full scale linearity of the Model 258 it is possible to make power readings of up to 19,999 digits (Current and Voltage each at twice full scale hence power at four times full scale.)

COMPUTER CONTROL-OPTICALLY ISOLATED IEEE-488 BUS OPTION

An optically isolated IEEE-488 option is available which allows the Model 258 to function as both a TALKER and as a LISTENER. Thus the instrument may be both controlled as to FUNCTION and RANGE and may supply its DISPLAY reading for remote reading and or calculation. Controlling software is simple and straightforward. (Option may be retrofitted.)

ISOLATED ANALOG OUTPUT

An optically isolated ANALOG is available. This circuit has a 1000 ohm output impedance. A full scale output on the Model 258 results in a 1.000V output from the ANALOG output. The output isolation is achieved by transmission of a pulse width modulated signal through an optical isolator and the subsequent demodulation of this signal. Up dating of the analog output occurs at a rate of ten pulses per second. Output from rear mounted, isolated BNC connector.

MEASUREMENT RATE/SETTLING TIME

The measurement rate of the Model 258 is normally set at 10 readings/sec (8.33/second for 50 Hz. operation).

The Model 258 is normally supplied so that it settles to within 0.5% of its final value within 1.3 seconds. At least a five to one reduction in this time is possible by reducing two filter capacitors from 10 uF to 1 uF. Such a reduction may lead to a slight increase in low frequency jitter.

DIMENSIONS and WEIGHT

Width:	290 mm (11.4 inches)
Height:	132 mm (5.2 inches)
Depth:	330 mm (13 inches)
Weight:	4.5 kg (10 lbs.)

RACK MOUNT AVAILABLE

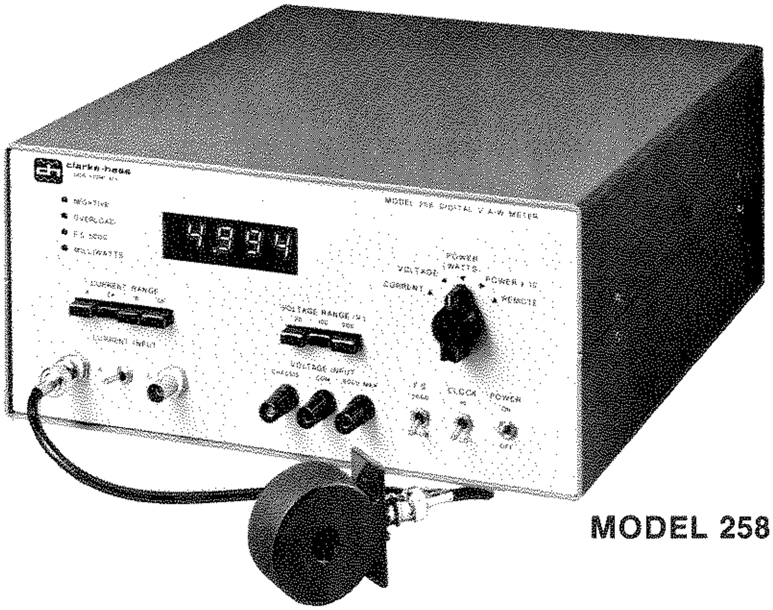
POWER REQUIREMENTS

95-105 V, 105-125 V or 210-250 V: 50-60 Hz. Less than 25 Volt-Amperes. Specify line voltage when ordering. Transformers are hard wired. Field modification requires soldering rather than changing a switch setting.

DIGITAL V-A-W METER

50 HERTZ—1 MEGAHERTZ

IEEE-488



MODEL 258

WIDE RANGE OF TRUE AVERAGE POWER READINGS

The Model 258 V-A-W meter provides broadband true average POWER readings from below 100 Hz to above 1 Megahertz. These AC coupled power measurements are independent of frequency, waveshape distortion or load power factor. From 50 Hz to 1000 kHz the power accuracy is specified as ±0.75% of the RANGE ±0.75% of the input Volt-Ampere product. This accuracy specification is for loads of any power factor. For zero power factor loads these specifications are typically conservative by at least a factor of five.

TRUE RMS BROADBAND CURRENT AND VOLTAGE READINGS

True RMS, waveshape and distortion independent measurements of the VOLTAGE and CURRENT are possible between 50 Hz and 1500 kHz. Accuracy of the AC coupled inputs from 50 Hz to 1000 kHz are specified as ±0.5% of the range ±0.5% of the input. From 1000 kHz to 1500 kHz the error specification is increased by a factor of 1.5. Typical accuracy is ±0.25% from 50 Hz to 1500 kHz.

EXPANDED RESOLUTION

A front panel switch allows one to set the full scale value of any range to 5000 digits. Thus a 100.0 W range may be expanded by a factor of five to offer 20 mW resolution.

HIGH CREST FACTOR

Both the current input transformer and the instrument can deal with highly distorted AC inputs. Except for the highest voltage range, which may be peak limited, all ranges can deal with full scale inputs having CREST FACTORS of at least FOUR (typically SIX). A CREST FACTOR of SIX means that the instrument will deal with an input having a peak value of SIX times the nominal RMS value of the range without causing peak clipping. Again, with the sometime exception of the highest voltage range, each range will deal with sinusoidal inputs of at least TWICE the nominal value of the range. That is a 200.0 V sinusoidal input will be correctly measured on the 100.0V range.

WIDE MEASUREMENT RANGE

The Model 258 has three VOLTAGE, four CURRENT, twelve POWER and twelve POWER X 10 ranges. The voltage ranges may be modified at the factory for full scale values between 100.0 mV and 500.0 V. There is a 25/1 limitation to the ratio between the highest and the lowest voltage ranges in a given instrument. Thus 20.00 V and 500.0 V are possible while 10.00 V and 500 V are not possible in the same meter. Full scale current ranges from 50.00 mA to 50.00 A are possible. Power ranges are formed by the product of the voltage and current full scale values. Special current input transformers may be supplied that offer greater sensitivity or clamp-on capabilities. There is normally a sacrifice of low frequency performance with such transformers.

WIDE CHOICE OF RANGES

Because all the decimal point and full scale information is kept in programable memories it is possible to provide CURRENT and VOLTAGE ranges in multiples of 1, 2, 2.5 or 5. Because POWER is the product of the VOLTAGE and CURRENT ranges a necessary restraint upon the possible combinations in a V-A-W meter is that the VOLT-AMPERE product must also be a multiple of these same numbers. Thus one can combine 250.0 mA with 10.00 V, or 20.00 V but not with 25.00 V or 50.00 V. To ease calibration difficulties the lowest voltage range should not exceed 25.00 V. A standard set of voltage and current ranges is listed on the other side of this page.

STRAIGHTFORWARD RESULTS IN PREVIOUSLY DIFFICULT MEASUREMENT SITUATIONS

The wide range and distortion handling capabilities of the Model 258 allow it to be used for measurements as diverse as ferrite core losses from 1 kHz to 1 MHz, high frequency lamp losses at 200 kHz, switching power losses in the PWM waveshape portion of a 150 kHz switching power supply, or RF power consumtpion in a 300 kHz induction heating system.

LOW CIRCUIT LOADING

The VOLTAGE input of the Model 258 has a normal input impedance of 1 Megohm in parallel with several pF. For CURRENT ranges equal or greater than 500.0 mA the impedance reflected in series with the load is 0.2 milliohms. For CURRENT ranges between 50.00 and 250.0 mA the reflected impedance is 20 milliohms.

IEEE-488 and ANALOG OPTIONS

The Model 258 may be equipped with an optically isolated analog output. An analog output of 1.000V corresponds to a full scale reading on the display for any function.

The Model 258 may be equipped with an optically isolated IEEE-488 card. This option allows collection of the data stored in the display as well as control of all functions, remote switching between all voltage ranges and remote switching between either pair of current ranges. (Special arrangements can be made to supply switching between all current ranges if required.) Readings are normally available via the bus at a rate of 10 per second.

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I. BASIC FEATURES, CONTROLS, AND OPERATION.

1-1. INTRODUCTION

The V-A-W Meter is a electronically sophisticated but easy to use solid state instrument. The meter is specified for POWER measurements from 50 Hz to 1000 kHz and for VOLTAGE and CURRENT from 50 Hz up to 1500 kHz. Within its frequency limitations the readings should be INDEPENDENT of WAVESHAPE or DISTORTION or POWER FACTOR.

This chapter of the Instruction Manual outlines the basic features of the instrument, the controls and terminals available on the instrument, and the configurations and connections necessary to make measurements with it.

Later chapters of the manual contain, information on current transformers, information on calibration equipment, the performance tests and calibration procedures, the theory of operation, repair procedures, the parts lists, and the set of schematic diagrams.

1-2. BASIC CONTROLS, INPUTS AND OUTPUTS.

The front panel CONTROLS for the Model 258 consist of the following:

The five position rotary FUNCTION SELECTOR switch.

The four CURRENT range pushbuttons.

The three VOLTAGE range pushbuttons.

The three toggle switches in the lower right hand corner.

The line power ON-OFF switch.

The CLOCK high/low switch.

The FULL SCALE 5000/Calibrated switch.

The front panel TERMINALS consist of the following:

The two black VOLTAGE input terminals.

The two BNC CURRENT input connectors

The single green CHASSIS connection.

The front panel OUTPUTS consist of the following:

The four digit DISPLAY.

The four indicator lamps.

NEGATIVE indicates that the POWER reading is negative. (Because of the TRUE RMS nature of the VOLTAGE and CURRENT readings they are always POSITIVE.)

OVERLOAD indicates that the output reading exceeds 1.5 times full scale hence the user should check that the operating controls are properly set. Readings are often VALID with this lamp lit.

F.S. 5000 indicates that the FULL SCALE 5000 switch is on.

MILLIWATTS indicates that the DISPLAY reading is MILLIwatts rather than watts.

* * * * * * * * *

The REAR panel of the instrument contains the following:

The line cord receptacle.

The 0.5 Ampere line power input fuse.

The output opening for the IEEE-488 or BCD/REMOTE options.

The output for the ANALOG option.(Only present if option is installed)

1-3. SPECIAL FEATURES

This section provides a brief introduction to several of the special features of the Model 258. This material should allow the user to avoid some apparent problems in their initial measurements with the meter.

POLARITY

The POLARITY indicator is only useful in the POWER or POWER X 10 cases. (Power flow may be in either direction while TRUE RMS voltage and current readings are always positive.) In the Model 258 reversing the direction of the passage of the current through the primary of the CURRENT TRANSFORMER will always reverse the sign of the POWER reading. If there is any initial doubt about the sign of the POWER reading then adding a resistor in parallel (or in series) with the load will resolve the question. For positive POWER the reading will increase. Negative POWER readings are still covered by the accuracy specifications.

FLASHING DISPLAY

Another aspect of the TRUE RMS operation is that the dynamic range of the squared signals is much greater than the range of the input quantities. That is a 30/1 range of input voltage leads to an internal signal variation of 900/1. This means that with an applied signal of 1/30 th of the full scale input the internal signal level - before the square root is taken - will only be (1/900)th as large as it would have been in the full scale case. As one might expect this large dynamic range will eventually lead to noise or jitter at low inputs. For VOLTAGE and CURRENT readings below 7% of the nominal full scale values the DISPLAY has been programed to FLASH rather than to provide a steady reading as it does in all cases for POWER or POWER x10. This FLASHING operation is normal it merely indicates that one has either no input or a very small input coupled with a CURRENT or VOLTAGE setting of the FUNCTION switch.

DISPLAY READING WITH NO INPUT.

Both a CURRENT and a VOLTAGE pushbutton should always be depressed. With no button activated one of the input amplifiers is left with an open circuited input and the DISPLAY reading may be both large and uncertain.

FULL SCALE: 5000/Calibrated Switch.

In order to provide the user with greater resolution on any range in which the nominal full scale value is not 5000 digits this switch allows the nominal FULL SCALE on any range to be increased to 5000 digits. The F.S = 5000 lamp should always indicate that this switch is in its 5000 position. Thus with a 10.00 volt input on the 20 V range and this switch in the 5000 position the reading should be 25.00, while with a 34.00 V input on the same scale the reading should be 85.00. Throwing this switch when the meter has a 100.0 watt input will change the display reading to 500.0. With the IEEE-488 bus option the serial poll indicates the position of this switch.

"FIVE DIGIT" OPERATION

V-A-W meter readings of up to 10,000 digits in VOLTAGE and CURRENT and of up to 20,000 digits in POWER are possible. This is true since, within the CREST FACTOR limitations, the linearity of the V-A-W meter circuitry allows both the VOLTAGE and the CURRENT channels to handle inputs of twice their nominal values. In cases of near unity power factor this will allow valid POWER readings of near 20,000 digits.(These readings require that the F.S. = 5000 switch be in the "5000" position.)

To interpret these readings one must note that the left most digit in the display is "blanked" when it is zero and that the OVERLOAD lamp comes on at about 1.5 times full scale. Because of the linearity a POWER reading of 205.0 watts is possible on the "CALIB." position of a nominal 100 watt range. If the "5000/CALIB" switch is moved to "5000" then the reading will become 25.0 with the left hand digit blanked and the OVERLOAD LAMP ON. This reading is interpreted as being 10250 digits which is 5 X 205.0 watts. If the input is increased to 230.0 watts then the display reading will become 150.0. Unexpectedly LOW display readings should always lead one to check the position of the 5000/Calib. switch.

POWER x 10

Since reducing the VOLTAGE and the CURRENT each by a factor of three reduces the POWER resulting from their product by a factor of nine the POWER-X-10 function allows one to get reasonable power readings in these "down scale" conditions. Whenever possible one should stay as far "up scale" as possible. Thus with a 24 V and a 70 mA set of inputs (assuming that the V-A-W meter has minimum ranges of 20 V and 50 mA) one should use the 20 V and the 50 mA ranges together with the POWER function instead of the 100 V and the 250 mA ranges together with the POWER-X-10 ranges. However with a 7 volt input and a 15 mA input for a unity power factor case one would only get a .105 watt reading on POWER while on POWER-X-10 the reading should be 105.0 mW. In general BOTH the VOLTAGE and the CURRENT should be at or below 40% of the nominal full scale value of a range before one uses the POWER-X-10 function.(With inputs with large CREST FACTORS one may have to reduce this limit further.)

CLOCK : High/Low Switch.

In order to provide its flat response from near DC to above 1000 kHz the V-A-W meter uses several circuit techniques that are discussed in Chapter VI. In all but one case these manipulations are completely "invisible" to the user. The CLOCK High/Low switch is provided as an escape from this special case. There is an internal chopping process at about 1670 Hz (LOW) or 1740 Hz (High) . If one operates at a frequency within several Hertz of this frequency, or of its odd harmonics, then jitter or beats may occur in the output display. Switching the CLOCK "HI/LO" switch to the other position will shift the internal chopping frequency by about 68 Hertz and the beats should disappear.

A C Coupling

The input to the CURRENT channel is AC coupled via the input current transformer. (The paint on the current transformer should NOT be counted on as voltage insulation.) The input to the VOLTAGE channel is AC coupled via a 10pF, 5000 V capacitor. The combination of a CT411 current transformer and the voltage channel AC coupling should allow measurements of loads with any power factor down to 50 Hz.

Chassis-to-COMmon Voltage

The Model 258 is a HIGH FREQUENCY instrument that should normally be operated with the minimum possible voltage between the "low" voltage lead connected to the COM terminal and the Chassis (connected to the GREEN terminal.) WHENEVER POSSIBLE THE COM LEAD SHOULD BE DIRECTLY CONNECTED TO THE CHASSIS BY CONNECTING THE GREEN TERMINAL TO THE ADJACENT COM TERMINAL.

In instruments supplied prior to September 1988 the Chassis and the CURRENT common point (the shell of the two BNC connectors) are connected internally via a 0.1uF capacitor with a 25V rating. With this capacitor present the application of 120V or 220V to the COM terminal - with the Chassis of the instrument connected to earth ground - is guaranteed to blow up the 0.1uF capacitor.

As of September 1988 the 0.1 uF, 25 V capacitor between the Chassis and CURRENT COM terminal is being reduced in electrical size to 5000pF and increased in voltage rating to 500V. Three other internal connections between the Chassis and the internal COM network, each of 1000pF at 1kV already exist. This means that the minimum capacitance between the Chassis and the COM terminal in new or modified instruments can be expected to exceed 8,000pF. At 100kHz a 8,500pF capacitor has a reactance of only 187 ohms hence at high frequencies one can not place a large voltage between the COM terminal and the Chassis without drawing excessive current from the source.

In addition, extra insulation washers have been placed between Q304 and Q305 and their heat sink; hence the instrument should sustain 250V RMS at frequencies up to 400Hz between the COM terminal and the Chassis. (At 400Hz the COM to Chassis capacitance will draw a current on the order of 5mA at 250V.)

There may be measurement situations wherein one does not wish to directly connect the Chassis and COM terminals but where circuit conditions will permit additional capacitance between these two points. Whenever possible additional capacitance should be added. In high frequency POWER measurement situations where the CURRENT is at or near full scale while the VOLTAGE is small with respect to full scale it is advisable to apply the CURRENT and the VOLTAGE "low" lead and with the VOLTAGE range on the highest scale (to reduce direct voltage pick-up) see that the POWER reading is indeed close to zero. If not some experimentation with line cord plug placement and/or with extra capacitance from the current transformer BNC connector to the toggle switch between the two BNC connectors may help to reduce the background reading. Another useful check is to see that the VOLTAGE reading is indeed the expected value on the various range settings.

II. OPERATION

2-1. CONDENSED OPERATING INSTRUCTIONS - GENERAL

This chapter outlines the procedures for making measurements of VOLTAGE, CURRENT, and POWER with the Model 258 Digital V-A-W Meter. In addition it points out some of the possible pitfalls in making such measurements.

The V-A-W Meter contains only one fuse which is the general power supply fuse that is located on the rear panel near the line cord receptacle. This rear panel fuse has a ¼ Ampere rating for 100 V or 115 V line operation and a ½ Ampere rating for 230 V or 240 V line operation. The Model 258 V-A-W Meter is supplied for operation from 50/60 Hertz power lines.

The V-A-W Meter has an INTERNAL CONNECTION between the COMmon VOLTAGE lead and the outside connector of the BNC CURRENT inputs. Connections to the instrument should be made so that NO EXTERNAL CURRENTS ARE CAUSED TO FLOW THROUGH THIS CONNECTION. That is the current transformer shell should be insulated from its primary winding.

The COMmon terminal should be connected to the "low" side of the circuit under test. To avoid unwanted capacitive coupling into the V-A-W meter via its external shield the CURRENT TRANSFORMER should also be placed on the "low" side of the load.

The Model 258 V-A-W Meter reads AC coupled VOLTAGE and CURRENT in a true RMS fashion. Since the ROOT MEAN SQUARE operation involves squaring then taking the square root a 31.6 to 1 range in the voltage or current being measured leads to a 1000 to 1 variation of certain of the voltages internal to the instrument. Each range should make accurate measurements of inputs that have a 40 to 1 range, that is from 2 times the nominal FULL SCALE value down to 1/20 th of the nominal FULL SCALE value. At 1/20 th of FULL SCALE a jitter term of ± 1 digit is normal. In general one is always better off making readings as far "up scale" as possible. The typical CREST FACTOR of SIX of the V-A-W meter allows one to stay "up scale" even with waveshapes that have pronounced spikes or peaks.

With no input the V-A-W meter should normally read 000. (The left hand zero is blanked when not in use.) The ZERO should be checked in the POWER position since very low values of voltage or current may have jitter. The display for VOLTAGE and CURRENT is "flashed" for reading below 1/20th of full scale to remind one that one is really reading off the calibrated area of the scale.

2-2. CONDENSED OPERATING INSTRUCTIONS - VOLTAGE.

To make a VOLTAGE measurement.

(a) Place the FUNCTION selector switch on VOLTAGE.

(b) Push in the appropriate one of the VOLTAGE RANGE selector buttons. The 20 V range is generally usable for sine waves up to 40 V RMS, the 100 V range is generally usable to 200 V RMS and the 200 V range is usable to 400 V RMS.

(c) Connect the desired voltage between the VOLTAGE COMmon (the low side of the voltage to be measured) and the right hand VOLTAGE terminal.

(d) Read the DISPLAY.

(e) Since the Model 258 is AC coupled it will NOT read DC voltages. For AC voltages the meter reads the TRUE RMS values of the voltage.(The low frequency -3dB frequency for the VOLTAGE channel of the Model 258 is about 1 Hz. The high frequency -3dB frequency is above 5 MHz.)

NOTE: The left hand VOLTAGE terminal (green) connects directly to the metal case of the V-A-W Meter.

NOTE: The input to the HIGH side of the VOLTAGE input of an instrument with voltage ranges of 20,100,and 200 V is equivalent to a capacitor of 15pF. Other voltage range combinations may require different values of input capacitance.

2-4 CONDENSED OPERATION INSTRUCTIONS - CURRENT

To make a CURRENT measurement.

(a) Place the FUNCTION switch on CURRENT.

(b) Push in the desired CURRENT RANGE selector button. Again each of the ranges may be used up to 2 times its nominal FULL SCALE value. As in the voltage case one should always try to keep the readings as far up scale as possible.

(c) Connect the load so that the CURRENT to be measured flows through the primary of the current transformer that is connected to the appropriate BNC connector.

(d) Read the DISPLAY.

LOSS IN THE CURRENT PATH

From the viewpoint of the circuit being measured the V-A-W Meter CURRENT input imposes a series impedance that varies with the TRANSFORMER selected and with the internal transformer termination supplied by the V-A-W meter. The table below indicates the coupled impedance for the current transformer/termination combinations that are normally supplied.

TRANSFORMER	Coupled Impedance	Assumed V-A-W Termination
CT-411 Single Turn	0.2 milliohm	30 kohm
CT-411 Ten Turns	20.0 milliohm	30 kohm

2-5. CONDENSED OPERATING INSTRUCTIONS - POWER

To make a POWER measurement one must set the FUNCTION selector switch on POWER , connect the voltage input, let the load current flow through the appropriate current transformer and depress the appropriate RANGE selector buttons.

There are several possible configurations with respect to POWER. The sign may be either positive or negative depending upon the direction of POWER flow. Reversing the flow through the current transformer will always reverse the sign. Depending upon whether the VOLTAGE leads are connected "inside" or "outside" the CURRENT transformer will determine whether the VOLTAGE input impedance or the coupled loss from the transformer is included in the measured POWER.

2-5. CONDENSED OPERATION INSTRUCTIONS - POWER x 10

The connections and operation of the meter are identical for the POWER and for the POWER x 10 cases. When both the CURRENT and the VOLTAGE are at or below 40% of their nominal full scale values then the POWER x 10 FUNCTION will provide an extra digit of resolution and accuracy for power readings.

2-6. POSITION OF CLOCK "HI/LO" SWITCH.

Unless one is attempting to measure a frequency that falls almost on top of the internal chopping frequency the position of this switch should not matter. If one has any question about its possible effect one should throw it back and forth and note that the two readings are the same. In the LO position the nominal chopping frequency is 1665 Hz while in the HI position it is about 1733 Hz. If beats or jitter occur in one position then the reading in the other position is the correct one.

III. CURRENT TRANSFORMERS AND CAPACITIVE ATTENUATORS

The Model 258 V-A-W meter uses a broadband current transformer as the input to its CURRENT channel. Therefore the proper use and calibration of the instrument requires an understanding of the properties and limitations of these devices.

Unless the proper precautions are observed the low frequency amplitude and phase performance of the V-A-W meter could be completely dominated by the characteristics of the current transformer that is used as the input device.

A conventional 100/1 current transformer consists of a one turn primary and a 100 turn secondary winding on a laminated iron core. If there is neither flux leakage nor any losses then the ampere-turns in the primary equals the ampere turns in the secondary so that a one ampere primary current produces a 10 mA secondary current. While such transformers suffice for the measurement of single frequency currents with analog meters they are often unsatisfactory when any one or more of the following properties matters: distortion, wide dynamic range, phase shift, or frequency response. Since all of these properties are likely to be important in most of the cases where a broadband V-A-W meter is employed such classic current transformers are usually inadequate as the current input device for a broadband V-A-W meter.

3-1 LOW FREQUENCY RESPONSE- LINEAR CASE.

In dealing with a current transformer, as with most other practical devices, one can not ever take anything for granted. Since there is an iron core one can not be sure that that phase shift and frequency response characteristics will not be at least partially level sensitive. In fact in all available devices they are. For the moment we ignore these effects and consider only the case where the device may be considered as linear and level independent.

From the linear viewpoint one can model the secondary of a transformer and that works into a resistive load by the circuit shown in Figure III-1.

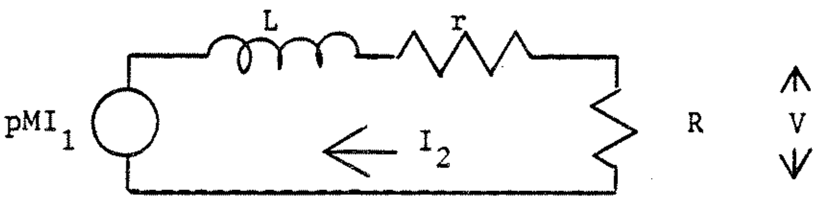

Figure III-1 Model for the secondary of a current transformer.

In Fig. III-1 M is the mutual inductance, L is the secondary inductance, r is the winding resistance of the secondary, and R is the load resistance. If one writes an expression for the secondary current then if R is a true resistance the voltage across the load will be a true representative of this current.

If one uses the operational notation p=jw then:

$$V_2 = I_2R = \frac{(I_1R)\ (pM/L)}{p + [(r + R)/L]} \qquad \text{(III-1)}$$

At a high enough frequency the p terms will dominate and the output voltage will be independent of frequency. When wL = (r + R) then the amplitude will be reduced to 0.707 of the high frequency value and will be shifted in phase by 45 degrees. If W is defined as (r + R)/L then one can tabulate the relative amplitude and phase shifts as a function of the ratio of the actual radian frequency,w, to the -3 dB radian frequency, W .

Table III-1

w /W	Amplitude/ A	Phase Shift in degrees
1.00	0.707	45.0
3.16	0.953	17.7
10.00	0.9950	5.71
31.62	0.9995	1.81
100.00	0.99995	0.57
1000.00	0.999999	0.057

3-1-1 LOW FREQUENCY PHASE SHIFT ERROR TERMS - LINEAR CASE.

From Table III-1 we see that by ten times the break frequency the maximum amplitude error that one can expect is 0.5%, while by 31.6 times the -3dB break frequency the maximum amplitude error is 0.05% Thus if one is attempting to measure CURRENT the transformer should be invisible by thirty times the break frequency. On the other hand if one is attempting to measure POWER, particularly in a low power factor case, then the phase shift becomes a much more serious problem.

As one can see from the data in this Table as one increases the frequency above the -3dB point the amplitude error decreases quadratically while the phase error only falls off linearly. Thus even at 100 times the break frequency one still has a phase angle from the transformer of 0.57 degrees or 1/100 of a radian. This much phase shift means that if one tries to measure the power in a zero power factor load one will get a reading of 1% of the input VOLT-AMPERES from the phase shift term even if the measurement frequency is 100 times the break frequency of the transformer. Thus a current transformer with a 1kHz break frequency will still be giving measurement problems with low power factor loads at frequencies as high as 200 kHz.

The Model CT-411 used with the Model 258 has a -3dB break frequency below 1 Hz hence the lowest frequency at which one would expect an error of 1% of the input volt-amperes product, even for a zero power factor load, would be above 100 Hz.

In the V-A-W meter the crucial thing is THE PHASE SHIFT BETWEEN THE VOLTAGE CHANNEL AND THE CURRENT CHANNEL rather than the phase shift of either channel. Therefore one can reduce the effect of the current channel phase shift by introducing a deliberate but equal phase shift in the voltage channel. By adding the proper R-C combination in the input of the voltage channel one can trade the introduction of an additional 0.5% amplitude error in the voltage channel at ten times the -3dB frequency for at least a ten to one reduction in the phase error at this and all higher frequencies. (Even if the phase matching between the channels is off by 10% one will still have a ten to one reduction in the differential phase error.)

In the present versions of the Model 258 the VOLTAGE input attenuator is capacitive. In this case the proper choice of a shunt resistor allows the phase matching of the two channels.

3-1-2 CHANNEL PHASE SHIFT IN WATTMETERS.

To see the general significance of the phase shift between channels one can consider the operation of any wattmeter in connection with a general linear load.

At any single frequency one can model any linear load as the combination of a series resistor (the loss term) and a series reactance (the energy storage term). To be specific let us assume that the reactance term is inductive. As we shall see the final result is just as valid for the capacitive case. Again the same general result may be obtained by assuming either a current or a voltage drive. To be specific we assume a driving current with the value $i(t) = I\sin(wt)$. This current results in a load voltage, $v(t)$

$$v(t)= (Ir)\sin(wt) + I(wL)\cos(wt) \qquad \text{(III-2)}$$

Now we assume that the combination of the wattmeter and its voltage or current sensing elements are not perfect with respect to internal phase shifts. For convenience we lump all of these phase shifts into one total differential phase angle, θ. When this phase shift is included then from the viewpoint of the circuit we may consider that the internal current term that is going to be multiplied by the voltage to produce the instantaneous power may be represented by the new variable $i(t)_3$:

$$i(t)_3 = I\sin(wt)\cos\theta + I\cos(wt)\sin\theta \qquad \text{(III-3)}$$

When the multiplier in the wattmeter has formed the product of the voltage and the current terms and the "DC" terms that are proportional to the average power are extracted and the the definition for I is changed from peak to RMS then the average power read by the properly calibrated wattmeter will be equal to:

$$P = I^2 r \cos \theta + I^2 (wL) \sin \theta \qquad \text{(III-4)}$$

Now if theta is small then cos θ may be approximated by one and the I^2r term will be the "correct" result for the power dissipated in the load and that the second term will be an error term. From Table III-1 we see that if we are at 31 times the break frequency then the cos θ term will be within 0.05% of unity for both the current and the voltage hence should not be worse than 0.1% in the power term and may reasonably be neglected. In the same frequency region it is a very good approximation to replace the sin O term by the angle in radians.(In this case theta is the DIFFERENCE between the current and the voltage phase shift terms.) When this is done the expression for power may be written as:

$$P = I^2 r \, (1 + Q \theta) \qquad \text{(III-5)}$$

where Q is the ratio of the load reactance to the load resistance. This expression is just as correct for the capacitive load case if the proper expression, that is Q = 1/(wCr), is used for Q in that case.

One may write an analogous expression for the case where one uses a parallel loss, R, and a parallel reactance term to model the load. In this case it is usually more convenient to assume a voltage drive. The resulting expression for the average power is: (Now Q equals the ratio of resistance to reactance.)

$$P = V^2 G \, (1 + Q \theta) \qquad \text{where } G = 1/R \qquad \text{(III-6)}$$

These last two expressions turn out to be very useful in understanding the limitations of wattmeters in general.

The first general observation that may be drawn is that the importance of the differential phase shift term, θ, is directly related to the Q of the load being measured. Thus in the case of a purely resistive load the phase shift error term disappears.

On the other hand if Q=100 , which corresponds to a POWER FACTOR of 0.01, then a differential phase angle of 1 milliradian (0.057 degree) will lead to an error of 10% of the reading. (Since the reading in this case should only be 1% of the input volt ampere product the error in terms of the volt ampere product will only be 0.01%) If one has achieved an input break point matching within 10% in the two channels, and IF ALL THE OTHER CHANNEL MATCHING IS PERFECT, then this much error would occur at 100 Hz.

3-1-3 MEASUREMENT AND/OR CORRECTION OF ERROR TERMS.

In attempting to use or to calibrate a V-A-W meter at low frequencies with low power factor loads then one must bear the PHASE SHIFT "error" term in mind. If one wishes to use a different CURRENT transformer as an input then one must give serious consideration to the properties of the new transformer.

Table III-2 indicates the -3 dB frequency, in Hertz, and the maximum current full scale display available from several of the transformers that might be considered for use with the Model 258.

TABLE III-2

Device designation	-3dB Frequency assuming a 50 ohm termination (except for CT-411)		Max. Sensitivity Single Turn V-A-W
CT-411	1 Hz		500.0 mA
Ion Physics CM-100-M	1200 Hz		50.00 mA
Ion Physics CM-10-M	60 Hz		500.0 mA
P6022 (Sensitive Position)	8500 Hz	(Ext.Term.)	50.00 mA
P6022 (Less Sensitive Position)	935 Hz	(Ext.Term.)	500.0 mA
P6022 (Direct - No Ext.Term.)	4000 Hz		50.00 mA

If any of the transformers,other than the CT-411, are to be used with the Model 258 then the addition of shunt resistance in the voltage box of a Model 258 with a capacitive voltage attenuator will allow one to increase the frequency of the pole in the voltage channel to match the break frequency of the transformer. (In a unit with a resistive input attenuator one can use an external coupling capacitor to achieve the same result.) Without such a correction the frequency at which low power factor errors equal the desired reading may be near the upper frequency limit of the Model 258.

Low frequency phase errors may be measured by using a "known" low loss load or a calibrator with a known value of phase shift between the voltage and the current channels. As an example of the low loss load case let us assume that one has a 5 uF, polypropylene capacitor that has a value of Q = 2,000 at 80 Hz. Now at 80 Hz the reactance of this capacitor will be 400 ohms hence with a 20 V drive the resultant current will be about 50 mA. The resultant I^2r term will 0.5 milliwatt, hence in the 5000 digit expansion position of the Model 258 the ideal reading, assuming a 50 mA and a 20 V set of ranges for the V-A-W meter, will be between 2 and 3 digits. Any actual reading on the V-A-W meter for this input, with this load, of between 0 and 6 digits indicates that the overall differential phase shift between the two channels is less than 0.5 milliradian or 0.0286 degrees.

3-1-4 LOAD POWER FACTOR CORRECTION OR "TUNING"

As we saw in Eq. III-5 the effect of differential phase shift errors in a wattmeter depend directly upon the Q of the load being measured. Thus if one can reduce the Q of the load one can reduce the importance of channel phase mismatching. A way to do this with an inductive load is to "tune" the load with a low loss capacitance so that from the viewpoint of both the generator and of the wattmeter the resultant load is closer to a purely resistive one.

From the viewpoint of the generator one can view this operation as one of "matching" whereby a series capacitive element lowers the overall impedance seen by the generator and raises the voltage available to the load, while a parallel capacitive element raises the overall impedance seen by the generator and raises the current available to the load. In measuring a ferrite core over a range of frequencies parallel matching may be appropriate at low frequencies while series matching is required at high frequencies.

If the losses in the added capacitive element are either small with respect to those of the element under test, or if they are known separately, then by making the wattmeter measurements of the composite load instead of the inductive portion alone one may be able to reduce the effective Q term to less than 5 or 10% of the original value. Such a reduction will reduce the effect of any differential phase shift error by a factor of 10 to 20.

3-2 LOW FREQUENCY RESPONSE - NON LINEAR

In addition to the linear low frequency problems caused by the interaction of resistance and inductance the fact that the transformer has an iron core causes the possibility that the phase shift and the frequency response characteristics will be at least partially level sensitive. In addition to such shifts there may be either gradual or sharp distortions in the output waveshapes as the frequency is reduced.

The type of low frequency distortion that occurs will depend upon the type of iron used in the transformer core and to some extent upon the construction technique employed in assembling the device. In some devices, such as the CT 411 transformer, a sharp distortion will occur at some low enough frequency that the integral of the ampere-turns over a half cycle causes core "saturation" and hence distortion. In other devices such as the Ion Physics or Tektronix units, the distortion is more gradual but just as real. This distortion means that even the best current transformers may have a number of different low frequency limitations.

Allowing any appreciable DC to pass through the transformer reduces the size of the AC signal that will cause distortion.

One can not make a general statement as to which low frequency limit will occur first. In fact both a fall off and phase shift from the "linear" network elements and distortion may occur at the same time. If a transformer is to be used within factor of TWO of its nominal lower frequency breakpoint then caution indicates that one should examine its output on an oscilloscope while it is excited with the waveshape in question and while it is loaded with the expected terminating resistor. Since "saturation distortion" is both level sensitive and frequency sensitive one needs to make this examination under the expected measuring conditions.

TABLE III-3

Onset of Low Frequency Core Saturation Distortion

Device Designation	Maximum Value over a half cycle for the integral of i(t) with respect to time. Ampere-seconds
CT-411	0.19 A-s
ION PHYSICS (CM-100-M)	0.0005 A-s
ION PHYSICS (CM-10-M)	0.01 A-s
ION PHYSICS CM-1-L	0.70 A-s
TEKTRONIX P6022	9. A-microsecond

It is believed that any of the devices listed in Table III-3 have, except for the onset of low frequency distortion and assuming that one stays above at least twice the -3dB break frequency, both amplitude and phase characteristics that are reasonably independent of amplitude. This statement can NOT be made for the run-of-the-mill current transformer.

3-3-1 HIGH FREQUENCY AMPLITUDE PERFORMANCE

The transformers supplied with the V-A-W meter will almost never impose a high frequency limit upon the system. Rise times of 10 nanoseconds and upper -3dB frequencies of 25-35 MHz or more are common. Again such performance can not be assumed for the ordinary current transformer that may be constructed of such low grade steel that it exhibits excessive loss by 200, 400, or 1000 Hz.

3-3-2 HIGH FREQUENCY PHASE PERFORMANCE

While the transformer itself does not generally present a phase problem at high frequencies the DELAY associated with the cable connecting the current transformer to the V-A-W may pose such a problem. At 1000 kHz (1 MHz) an additional length of 30.5 cm (12 inches) of RG-58A/U cable will have the effect of adding about 1% of the input volt-ampere product to the output power reading in low power factor measurements. This effect is linear with frequency so that at 100 kHz the effect with only be one tenth as large. However if one is trying to make calibrated power measurements at high frequencies in low power factor situations then one MUST NOT CHANGE CABLE LENGTH IN MID-STREAM. The instrument is normally supplied and calibrated with a 61 cm (24 inch) cable to connect the current transformer to the instrument.

In general changing the length of the voltage leads is much less critical since their high terminating impedance prevents appreciable phase shifts in them.

3-4 PEAK CURRENT OR CREST FACTOR LIMITATIONS

As long as the low frequency distortion limitations are avoided the transformers supplied with the V-A-W meter usually have peak current carrying abilities at least 1000 times their RMS rating hence they almost never impose any peak or crest factor current limits.

3-5 REFLECTED LOADS INTO THE CIRCUIT BEING MEASURED

In the case of an ideal current transformer one reflects the sum of the load and the secondary winding resistance through the square of the turns ratio to find the effective series resistance placed into the primary circuit. As a practical matter the devices supplied with the V-A-W meter may have a different effective turns ratio from the load viewpoint and from the current reduction viewpoint. In addition an internal load may have to be considered when figuring the reflected loss. Table III-4 indicates the reflected loss terms to be expected from some of the current transformers that could be used with the Model 258.

TABLE III-4

Device	Reflected Load assuming a 50 ohm load. (except for the CT-400)
CT-411 (Single Turn)	0.2 milliohm
CT-411 (Ten Turn Primary)	20 milliohm
ION PHYSICS (CM-100-M)	22.6 milliohm
ION PHYSICS (CM-10-M)	0.57milliohm
ION PHYSICS CM-1-L	0.53milliohm
P-6022(either position)(Ext.Term.)	30. milliohm

3-6 CAPACITIVE ATTENUATORS

It can be shown that most of the quantities of interest about a capacitor or inductor can be derived from measurements of the current, voltage, and power passing through it or into it. If one assumes that the current is sensed with a broad band current transformer then one should sense the voltage in a manner that both matches the low frequency amplitude and phase characteristics of the current transformer and that causes minimal loading of the test circuit. (The current transformer used with most Clarke-Hess V-A-W Meters has a low frequency response that may be represented by a zero at the origin and a pole at about 1Hz.)

While inductive voltage dividers are used as very accurate voltage dividers over narrow ranges of frequency no commercial units are known that will deal with the 4-5 decades of frequency that are required by the broadband V-A-W meter. (What is required over this whole frequency range is amplitude flatness within ±0.1% or ±0.2% coupled with high frequency phase variations on the order of 1-2 milliradians and low frequency phase variations in the voltage channel that match those of the current transformer.)

If these arguments exclude transformers and other inductive devices as possible input transducers then one is left with resistive, capacitive, or R/C attenuators. The classic instrument approach to the attenuator that must handle DC is the "compensated" R-C attenuator. A simple resistive attenuator is not practical if one tries to operate at any sort of reasonable impedance level and over a wide range of frequencies. This is true since some stray capacitance will always occur across the high impedance. For example 1 pF of stray capacitance across 1 Mohm will cause 45° of phase shift by 159 kHz and 5.7° by 15.9 kHz.

The "compensated" attenuator approach admits of this stray capacitance, indeed often adds extra capacitance to "swamp" or stabilize the stray component. It then adds additional capacitance across the shunt resistive element to make the shunt R-C time constant equal to the high impedance series R-C time constant. When this is done then the pole and zero in the transfer function cancel and the attenuator is theoretically frequency independent. Difficulties with this approach are several fold. One is that practical values of shunting capacitance often force the pole and zero of the transfer function to occur in the frequency band of interest. Therefore a failure to get them adjusted to exactly the same frequency results in phase and/or amplitude bumps. Another practical difficulty is that some of the small capacitance across the high impedance series arm is apt to be distributed rather than lumped into a single element and some of this capacitance may be directly to ground rather than straight across the resistor. These distributed terms will not be cancelled out by a single shunt capacitance.

When only AC signals need to be dealt with then one can leave out the resistive elements. In this case one has a capacitive attenuator. Such units have long been in use as the method to reduce very high voltages down to manageable levels. If such an attenuator works into a resistive load then it will have a low frequency break point. The trick is to tailor the low frequency response so that it matches that of the current transformer. It turns out that with practical values this can be done.

When dealing with a capacitive attenuator one must find a reasonable way to characterize it in terms of the capacitors used to construct it. (In the compensated resistive attenuator the equivalent loss terms of the capacitors generally do not matter since they are swamped out by the deliberate resistive elements in parallel with them.)

To examine this problem consider the capacitive attenuator that can be modeled - at a single frequency - as a series arm with a capacitor,C, that has a parallel loss term, R, and a shunt arm that has capacitor k, with a parallel loss term, r, . Then add a further loss term, RR in parallel with r. If the appropriate conductance term for each resistor is written as the equivalent "gee" term then the condition for no variations in amplitude or phase shift as the frequency is varied is that C/G = k/(g+GG) or that $Q_C = Q_{kk}$ where Q_{kk} is the Q of the capacitor k when loaded with the extra resistor, RR.(This extra physical resistor both provides a DC return for the input amplifier in the voltage channel of the V-A-w meter and if the proper value is selected will provide the desired low frequency phase response. Its choice will be discussed subsequently.)

In the capacitive attenuator one does not deliberately add the components R and r, these are the inherent losses in the capacitors. It follows that one does not in general have any values for these components or does know how they may vary with frequency. Therefore it often easier to think in terms of of the loss in the capacitor as expressed by dissipation factor or its reciprocal, Q.

If the values of the loaded Q's are reasonably high, as they must be to produce a decent attenuator, and if k is much larger than C as it will be in a 100/1 or larger step-down attenuator, then one can show that the transfer functions for the assumed network may be approximated very closely by :

$$(v_o/v_i) = [C/(C + k)][1 + j(1/Q_{kk}) - j(1/Q_C)] \qquad \text{(III-7)}$$

Thus when the values of Q are large the amplitude ratio of the attenuator reduces to [C/(C+k)]. When the two Q values are equal then there is no phase shift, while if they differ but are both high the net phase angle in radians will be equal to the ratio of the imaginary to the real part. Thus 10^3 times the difference of the reciprocals of the Q 's will yield the phase angle in milliradians.

To keep the net phase angle from the attenuator below 1 milliradian requires that the Q's of the two capacitors be matched as follows:

Q_{max}	20.4	52.6	111	250	428	666	1000
% difference	2	5	10	20	30	40	50

To achieve a phase error of less than 100 uradians with the same degree of matching will require that the initial Q values be ten times larger.

What a phase error of 1 mradians means in terms of the voltage attenuator in a wattmeter is that if one has a full scale input of say 5000 digits of volt-ampere product then there will be a 1/1000 or 5 digit error. In terms of the input V-A product this is an error of 0.01%. In terms of a load with a power factor of 0.001 it is a 100% error in the reading. To reduce this error to 10% of the reading will require that one reach the 100 uradian contour. If one can keep the Q values of both capacitors above 10,000 then the worst phase error will always be less than 100 uradian. With loads with power factors greater than 0.01 one will not get an error of more than 1% of the reading from this source.

From this discussion it follows that one does not make a decent capacitive attenuator from any old capacitors that happen to be lying around the laboratory. It is necessary that one have the means to measure the Q of the capacitors over the frequency band of interest. It is further necessary that the Q values be high and that if they vary with frequency that the two different values have similar variations with frequency.

It turns out that many "good" capacitors tend to have Q values that are reasonably independent of frequency over quite wide ranges of frequency. Thus Q is a much more convenient term to consider then is the resistance itself. If Q is frequency independent then at low frequencies the resistive terms from the capacitors will tend to be much larger than the real resistance, RR, and hence may be ignored..

To deal with the low frequency response one considers only C,k, and RR. In this case the transfer function has a zero at the origin and a pole at GG/[k + C]. If k is 1990 pF, C is 10 pF, so that one has a 200/1 attenuator then a value of 82 Mohms for RR will lead to a -3dB frequency of about 1 Hz which matches the response of the assumed current transformer almost exactly. (In practice one should choose RR on the basis of experimental low power factor measurements in the 50-400 Hz region.)

With this approach one may construct voltage inputs with unity gain attenuators for full scale values of between 50.00 millivolts and 1000 millivolts, or plug-in capacitive attenuators with 1/1, 10/1,100/1, or 200/1 ratios.

For instruments with no more than three voltage ranges and a variation between the full scale values of these ranges of 25 or less one builds the attenuator into the instrument. If one wishes either more ranges or a wider dynamic range then external plug in attenuators are possible. (Almost by definition the plug in units will be more prone to poor connections and other practical difficulties, hence they are NOT recommended unless they are really necessary.

Whether internal or external there are some practical constrains on what is possible. If one wishes to keep the value of RR and of the low frequency breakpoint both constant then the total of C and k must always stay close to 2000 pF. Thus a 200/1 ratio will require a 10 pF series element with a nominal 2000 pF shunt element. If one wishes to go to a 500/1 ratio while not reducing the input capacitance below 5 pF (too small a value may be hard to control with respect to stray capacitance) then the shunt element will have to be 2500 pF and RR will have to be loaded down to 65.6 Mohms.

If multiple attenuators are used then decimal point and/or full scale PROM's can be supplied for both attenuators however there is no way to provide internal switching between the PROMs when switching external attenuator boxes. With a computer connected to the V-A-W meter then as long as the computer "knows" while attenuator is in place the decimal point placement may be done automatically.

At the highest frequencies the capacitive input circuit may take more current than a resistive attenuator. For example a compensated attenuator consisting of 1 Megohm in parallel with 1.5 pF operating at 1 MHz will look like 1 Mohm in parallel with a reactance of about 106 kohms. Therefore a 500 V,1 Megahertz source will have to supply about 5mA of reactive current as well as 250 mW of power. If one substitutes a capacitive attenuator with a 5 pF input capacitor then at 1 MHz one will draw 15.7 mA of reactive current from a 500 V 1000kHz source. There is no general rule that says which type of situation will be most satisfactory from the source viewpoint. At lower frequencies the capacitive attenuator will take less current than the resistive one.

If the attenuator is connected "outside" the current transformer winding then this extra current will not be sensed by the current input. In this case the drop caused by the load current flowing through the winding and the reflected resistance of the current transformer will be included in the measured voltage. In the case of 50 or 250 mA current inputs the impedance in the current transformer branch is on the order of 100 milliohms hence one should generate worst case error voltages of less than 25 mV and worst case power errors of about 6mW. With higher current inputs and thus single turn primary operation for the current transformer this impedance should drop to less than 5 milliohms hence the drop will normally be negligible.

If the voltage leads are connected directly across the load then the extra reactive current taken by the attenuator will be registered by the current reading however to the extent that this current is purely reactive there should be essentially no error in the power readings.

IV. CALIBRATION EQUIPMENT AND TECHNIQUES.

The Model 258 is a "state of the art" instrument therefore to calibrate it requires equipment or techniques that may not be completely familiar even in a well equipped calibration laboratory. For this reason it seems desirable to include a discussion of instruments and ideas that may be useful before going through the detailed performance tests and calibration procedures outlined in the next chapter.

To calibrate a Model 258 at a single frequency one needs "absolute" sources of VOLTAGE, CURRENT, and POWER. To insure constant outputs over the required frequency range one requires sources of these quantities that are "flat" from 50 Hz to 1500 kHz. In addition one requires at least some known phase shift situations at specific frequencies in the same frequency range. (Note that the "flat" quantities do not have to be "accurate" as long as they are constant with frequency.)

The chapter will begin with a discussion of some of the commercial equipment that is suitable for calibrating an instrument such as the Model 258.

4-1 VOLTAGE SOURCE AND/OR MEASUREMENT

There are several approaches to obtaining a "flat" voltage over a range of frequencies. One is to put the problem back upon a manufacturer. In this case one buys what is known as a "voltage calibrator". Such a device is supposed to produce a voltage within some specified amplitude limits over some specified frequency rang. In addition the calibrator will have some allowable output current or power limitation and will have some distortion limits.

The second approach is produce the desired voltage over the desired frequency range, but to admit that it is probably NOT completely "flat" hence it must be measured and then one must either adjust the amplitude at each frequency or one must apply a correction factor at each frequency.

In either approach one must take care that the measuring part of the system operates in the same fashion as the device under test since "flat" with respect to "average" and "flat"with respect to "peak" and "flat" with respect to "RMS" are usually NOT the same.

A brief explanation of the workings of the VOLTAGE channel in the Model 258 will help in deciding what voltages are really necessary to check or to calibrate a Model 258 V-A-W meter. The Model 258 has three voltage ranges. The nominal full scale magnitudes of these ranges may vary from 1 V to 200 V with some set such as 20 V/ 100V/ and 200 V or 10 V/ 20 V/ and 100 V being typical. Whatever the set of ranges all the voltage inputs share a common input attenuator and a common input buffer stage. The division into separate ranges is done in a low impedance switching section (all impedances below 250 ohms) at the output of the buffer stage. Each range has a separate full scale and 1/20 th full scale amplitude control. Since the only place the three VOLTAGE ranges differ is in the low impedance switching network one has only a single set of frequency controls for the VOLTAGE channel. Thus while three different levels are convenient to check or to set the absolute values of the three ranges only one wideband VOLTAGE level is necessary to check the flatness of all three ranges.

4-1-1 COMMERCIAL VOLTAGE CALIBRATORS.

A Fluke Model 5200 A C Calibrator is an example of a commercial voltage calibrator that will provide a "flat", true RMS voltage source up to 1200 kHz for a 1V, 2V, or 10V range. For a 10 V output on the 10 V range the nominal accuracy from 100 kHz to 1000 kHz is specified as ±0.36% which is three times the specified accuracy of the Model 258. (The typical accuracy of the voltage channel of the Model 258 is expected to be equal or better than 0.36% from 50 Hz to 1500 kHz hence in fact the use of the Fluke Model 5200 as a calibration source will not provide the factor of at least 5 which one would like to have between the calibration instrument and the unit under test.)

Another commercial AC voltage calibrator that covers the desired frequency range is the Julie Research AC-125 which claims a ±0.2% accuracy for frequencies up to 1100 kHz at amplitudes up to 12 V.

With either of these units and a V-A-W meter in which the lowest full scale is 10 V one will have full scale capability. When the V-A-W meter's lowest scale is the 20 V range then one is going to be working at about half scale (2500 digits in the 5000 digit full scale configuration) in voltage and in power.

4-1-2 COMMERCIAL GENERATORS

If one wishes to try the generator/meter approach then again there are several possibilities. The first approach is to obtain a generator with an adequate output voltage and current capability directly, the other path is to generate the desired frequency coverage and then to use a separate broadband amplifier to obtain the desired output levels.

As a voltage source for either possibility a number of commercial function generators will supply a reasonably flat sinusoidal voltage output up to at least 1000kHz. This source can then be measured with a wideband true RMS voltmeter. Function generators by companies such as WAVETEK, H-P, or EXACT can produce up to 30-32 V peak to peak sine wave into an open circuit. This means a peak voltage of 16 volts and an RMS voltage of about 11 V. With a 10 V scale on the V-A-W meter this yields a full scale reading however with a 20 volt scale one must do the calibration at half scale. Since this is at a level of 2500 digits, assuming the full scale equal 5000 digits position is used, it is possible to see a variation of 0.04% with the V-A-W meter. This resolution turns out to beyond the accuracy specifications of most commercial true RMS voltmeters that might be used to monitor the function generator output.

Before using a function generator output as a voltage source for calibration purposes one should examine it on a high frequency oscilloscope to make sure that it is relatively "clean". If there is either high frequency ringing or undue distortion then one must either filter the waveshape before using it - this will undoubtedly introduce more amplitude variation that was present initially - or must prove that this extra "garbage" is being treated the same way by the external measuring circuit and by the V-A-W meter. Since this last proof may be difficult filtering is the better approach.

4-1-3 COMMERCIAL RMS VOLTMETERS.

A number of companies such as Fluke, H-P, Guildline, and Racal-Dana, to name a few, have true RMS meters, both analog and digital, that are specified to 1 MHz. While the claimed accuracy for the DC portion of the digital meters is often in the parts/million region, the 100 kHz to 1 MHz AC accuracy is often only in the range from 0.7% to 3 %. The analog meters tend to have a ±1% accuracy claim, however one must either have a very fine vernier on the generator, in order to keep adjusting the level to a constant mark on the meter, or one must try to read the analog meter between marks, or one must treat the analog unit as an RMS converter and read its output on a separate DC meter.

4-1-4 THERMAL TRANSFER STANDARDS AND THERMOCOUPLES.

A second approach to measuring the output of a generator or amplifier is to use a thermal transfer standard instrument or its equivalent which is a thermocouple/attenuator combination. Ballantine Laboratories, Julie Research, and Fluke all produce thermal transfer standard instruments. As an example a particular Fluke A55 20 V Thermal Converter claims a -0.004% AC/DC difference with an uncertainty of ±0.05% out to 1000kHz and an AC/DC difference of -0.011% with an uncertainty of 0.1% out to 10 MHz.

If one uses a Thermal Converter or a separate thermocouple with an appropriate current limiting resistor, then its output must be read either directly on a sensitive and accurate DC voltmeter or its output must be amplified with a chopper stabilized DC amplifier before being applied to the DC voltmeter. As an example of what is possible with a thermocouple the H-P Model 11050A Thermocouple Assembly (No longer listed in the H-P catalog) claimed a ±0.07% accuracy from 20 Hz to 1000kHz.

A practical problem, beside that fact that such measurements, if made manually, are generally rather time consuming, with the transfer standard or thermocouple approach is that the thermocouple element may require from 2.5 mA to as much as 20 mA of drive current. (The Fluke A55, for example requires 5.55 mA) This extra current must be supplied by the test generator. With a 50 mA load current an extra 20 mA may cause a non-trivial voltage drop.

A typical thermocouple will produce about 7 mV of DC output for a full scale input. With a six digit DC voltmeter and either a 100.000 mV or a 200.000 mV range this combination will yield 7000's digits of resolution.

The same resolution, with more potential noise, can be obtained by feeding the thermocouple output through an internally chopper stabilized integrated circuit amplifier, such as the Intersil 7650. If the amplifier has a gain of ten then a five digit meter with a 100.00 millivolt scale will again offer a resolution of 7000 digits. If the generator output is reasonably constant with frequency then the thermocouple output will be nearly constant with frequency and the primary voltmeter or amplifier properties of interest become stability and regional linearity rather than absolute accuracy.

In making thermocouple measurements one must remember that for small variations of the input voltage the DC output may be assumed to vary as the square of the input hence the DC output variations will be TWICE the actual AC input VOLTAGE variations. (For large variations one can not assume that the output vs input relationship is exactly square law. For absolute measurements the exact law must be determined for each thermocouple. Since POWER is proportional to the square of the VOLTAGE small variations in the thermocouple output should be proportional to POWER variations.

A computer controlled set-up in which the generator frequency is adjusted by the computer then both the V-A-W meter under test and the DC output meter which is monitoring the output of the thermocouple are read by the computer, say via the IEEE-488 bus greatly eases such an amplitude flatness testing operation. The computer may of course be programed to average a number of readings at each frequency and thus to provide additional filtering. It can also be programed to do the necessary square rooting and normalization with respect to a reference frequency.

4-2 WIDEBAND CURRENT SOURCES.

There are several basic ways to approach the wideband current source problem. The most fundamental one is to produce a wideband voltage source with adequate power output to drive a resistive load that will carry the desired current. From the V-A-W meter viewpoint this approach has the great beauty that it provides VOLTAGE, CURRENT, and POWER outputs all at the same time. The two fundamental problems are to obtain the non-reactive resistive load and to obtain the wideband, low output impedance, flat amplitude, amplifier or generator.

The other possible way to tackle the current source problem is build a wideband current amplifier and then to couple this with a broadband sampling circuit - either a coaxial shunt or a broadband current transformer - to a broadband true RMS converter, and an automatic gain adjusting circuit so that one keeps the current constant as the frequency is varied. What has just been described is a wideband current calibrator.

4-2-1 COMMERCIAL CURRENT SOURCES

Most high current commercial current sources, or voltage to current converters are limited to quite low frequencies. For example the current outputs of the Fluke 5100 B are limited to 5 kHz. Other commercial "high" current amplifiers tend to have even lower limits on their frequency response. Within the current availability limits one does better with the Model 5100's voltage channel output plus a non-reactive resistor. A Fluke 5100B, for example can normally provide up to 50 mA from voltages up to 19.999 V up to 50 kHz, while a Fluke 5200 can provide up to 50 mA from voltages up to 10 V up to 1000 kHz. (At 1000 kHz the output impedance of the Model 5200 is NOT necessarily negligible)

Clarke-Hess has "in house" current calibrators that provide currents of 5,50, and 500 mA from 50 Hz up to at least 1200 kHz and a current of 5 A up to at least 600 kHz.

4-2-2 AMPLIFIER/RESISTOR COMBINATIONS

Clarke-Hess has an MOSFET output amplifier/non-inductive resistor combination that can supply up to 20 V RMS into resistive loads of 400,100,40, and 10 ohms. This means that one can supply currents of 50,200,500, and 2000 mA and powers of up to 40 watts. These outputs (except for the 2 A case) can all be supplied from 100 Hz up to 1200 kHz. The amplifier has an internal DC balancing circuit that holds the DC output to less than ±20 mV over the whole frequency range. When driven from a properly filtered function generator the internal fine amplitude vernier control allows one to keep the voltage output constant within 1 part in 5000 IF one has a measuring instrument with the necessary accuracy. The voltage scale of the Model 258 will provide the necessary resolution. The 20V range on a properly calibrated Model 258 is typically accurate within ±15 digits out of 5000 digits (±0.3%) over the 1-1000 kHz range hence lacking a better measuring instrument one may use the VOLTAGE scale of the Model 258 together with a amplifier-resistor combination as a means of providing a calibrated source of CURRENT and of POWER.

4-3 PRACTICAL CONNECTION, MEASUREMENT, AND ERROR PROBLEMS

With the amplifier-resistor combination the current is ideally produced via a non-reactive load hence the product of the CURRENT and the VOLTAGE should indeed be POWER. The problem is to sample the VOLTAGE across the load resistor without disturbing the CURRENT through it, while at the same time sampling the CURRENT through the load resistor without disturbing the VOLTAGE across it.

The optimum connection of the voltage leads with respect to the current transformer depends upon the load impedance,the input configuration of the current transformer, and the input impedance of the V-A-W meter..

If the voltage channel of the V-A-W meter, or of any other voltmeter, is connected directly across the load resistor then one must guarantee that NO current flows from the LOW side of the voltage channel directly back to the LOW side of the amplifier without passing through the CURRENT transformer. In general such a guarantee is difficult to provide, particularly at frequencies above 200 kHz. With this connection across the load resistor the CURRENT transformer would "see" the CURRENT that flows through the input impedance of the V-A-W meter or other voltmeter. If one is dealing with a Model 258 the normal input impedance is 1 megohm hence at 20 V this extra current can not exceed 20 microamperes. If one attempts to use a thermocouple or other "low" impedance instrument to monitor the VOLTAGE then this extra CURRENT may indeed become very significant.

If the VOLTAGE connection are made from the high side of the load to the other side of the sampling loop then the effective magnitude of the load resistor has been modified by the sampling loop.

This problem will be more apparent the lower the load impedance. For example for a 0.1% amplitude error with a 10 ohm load the extra resistance introduced by the sampling loop must be less than 10 milliohms while the extra inductive reactance must be less than 440 milliohms. With both of these restrictions can usually be met with a short heavy piece of braid. (At 1000 kHz it only take about 67 nanohenries to produce an inductive reactance of 440 milliohms) . Table III-4 in Chapter III indicates the magnitude of reflected impedance that one can expect from different current transformers. Obviously these impedance problems will be less severe when one goes to a larger load resistor and thus to a smaller load current. Moving to a lower CURRENT range may cause one to change the number of turns used for the primary of the current transformer which may in turn increase the reflected impedance.

As another example assume that one wishes to check the 50 mA CURRENT and POWER ranges using a CT-411 transformer with a TEN turn primary and a 400 ohm load resistor. The magnitude of the resistance of the sampling loop will depend upon the wire size used. With # 20 wire this resistance can easily be made to be less than 50 milliohms which will add to the reflected impedance from the transformer of 20 milliohms. Since this total is less than one part in 5000 of the load impedance one would expect to ignore it. The inductance of the TEN turns will be on the order of 1.7 microhenries hence by 1 megahertz it will have an inductive reactance of about 10.5 ohms. When compared to the 400 ohm load this increase in impedance will increase the magnitude of a 5000 digit display by 1.5 digits at 1000 kHz. This means that the VOLTAGE reading may be unchanged but the CURRENT reading will be reduced by 1.5 out of 5000 digits from what one would have expected from dividing the VOLTAGE by 400 ohms.

With respect to POWER the inductance will also introduce a phase shift of 1.43 ° at 1000 kHz. This phase shift should cause a 1.5 digit decrease in the POWER reading FROM THE PRODUCT OF THE VOLTAGE AND THE CURRENT READINGS. (This assumes that the internal phase shift between the two channels is zero and that the load resistor itself is completely non-reactive.

If the instrument has an internal differential phase shift then the "error" term may add or subtract hence the actual reading might be 1.5 digits higher or lower than the expected product.)

In any case the expected errors in either of these cases are small with respect to the accuracy specifications of the V-A-W meter, hence this is a possible connection.

Unless one is dealing with very low impedance loads then it appears that connecting the VOLTAGE from the high side of the load resistor to the "far" (the amplifier ground side) of the CURRENT sampling loop offers the least troublesome set of errors.

V. PERFORMANCE TESTS AND CALIBRATION PROCEDURES.

This chapter is concerned with checking the performance of the Model 258 and with the recalibration of any functions that may have been disturbed by component replacement. The EVEN sections of the chapter outline a performance test for a particular range or function or input while the following ODD section outlines the procedure to followed when recalibrating this range or function. IN OUR EXPERIENCE THE MODEL 258 RARELY REQUIRES RECALIBRATION UNLESS SOME PART HAS BEEN REPLACED. THE USER IS URGED TO BE VERY CERTAIN THAT RECALIBRATION IS REALLY REQUIRED BEFORE STARTING ANY PROCEDURE.

5-1. CALIBRATION EQUIPMENT AND STANDARDS.

All of the performance tests assume that one has placed the 5000/CALIB. switch in the 5000 position so that the full scale reading is always 5000 digits. In this configuration the Model 258 has a resolution of at least 1 part in 5000 or 0.02%. It will be apparent that unless the calibration equipment employed is stable and accurate to beyond this limit that one may be measuring the variations in the calibration equipment rather than checking the Model 258.

The tests may be considered in three parts. There are single frequency accuracy tests, there are AC "flatness versus frequency" tests for VOLTAGE , CURRENT, and resistive POWER, and there are tests for proper operation in the POWER case with low power factor loads at various frequencies.

Another aspect that must be kept in mind while making any comparisons between the Model 258 and other meters or calibrators is that the Model 258 is TRUE RMS AC reading. For example if a full scale sinusoidal voltage has a 2% third harmonic distortion added to it the reading of a Model 258 will increase by one part in 5000, while if the same distorted voltage is read with an ideal full wave, average reading meter the reading may vary by ±100 digits out of 5000 depending upon the phase relationship of the distortion to the fundamental. Even 0.1% odd harmonic distortion from a generator or a coupling transformer may cause a 0.1% difference between the Model 258 and some other meters that are highly accurate in their own realm.

The full scale readings of a Model 258 set on CURRENT, VOLTAGE, or RESISTIVE power are typically held to well within (a factor of at least five is typical for VOLTAGE or CURRENT) ±50 digits from the lowest specified frequency out to beyond 1500 kHz (1.5 MHz). For operation near full scale the specified accuracy from 50 Hz to 1000 kHz is ±1% for VOLTAGE or CURRENT and ±1.5% for POWER. In terms of digits out of 5000 digits these percentages turn into ±50 digits for VOLTAGE or CURRENT and into ±75 digits for POWER or POWER X 10. As pointed out in Chapter IV several companies produce voltage calibrators that offer better than 0.5 % accuracy to at least 1,000 kHz.

As a practical matter commercial instruments that can provide 50 mA or 500 mA, at 100 kHz or more are rare. In fact many commercial current calibrators have an upper frequency limit of 5 kHz, 1 Khz or even less. If a voltage calibrator has enough output current capability, say at least 25 mA, then such a generator may combined with a non-reactive resistor to provide a current source to investigate the flatness of the the 50 mA range of the Model 258.

To completely perform the tests outlined in this chapter one requires some set or combination of equipment as described in Chapter IV that provides CURRENT and VOLTAGE and that operates satisfactorily out to at least 1000 kHz. If the equipment is not of the self contained calibrator type then one also requires comparison meters that are accurate to within at least ±0.3 % out to at least 1000 kHz.

5-2. PERFORMANCE TESTS - METER "ZEROS"

The downscale performance of the Model 259 V-A-W meter must be considered in two separate parts. One part for VOLTAGE and CURRENT and another part for POWER and P X 10. Both the POWER and the POWER X 10 functions have individual zero controls and both should indeed read close to 000 with no inputs.

In a high field environment the high input impedance and broadband of the VOLTAGE input may lead to pickup that is interpreted as an error in the zero reading. If such seems to be the case then one should switch to a higher VOLTAGE range or short the VOLTAGE input before drawing any conclusions.

Both one CURRENT and one VOLTAGE button should be depressed during all attempts to read the POWER zeros.

Since the POWER accuracy specifications have a ±0.75% of full scale term the POWER or POWER X 10 "zero" readings could lie within ±37 digits of 0000 and still meet this requirement. Normally the POWER and POWER X 10 zeroes are expected to be within ± 1-2 digits (on the basis of 5000 digits for full scale) of zero.

Since the VOLTAGE and CURRENT ranges are all true RMS their far downscale values are noisy. Because of this fact the performance for these functions is only specified between RMS values of 1/10 and twice the nominal full scale values. For best overall linearity one adjusts the individual range "zero" controls for these functions at 1/20th of full scale and lets the no input or true "zero" values be whatever they turn out to be. Thus with no inputs to the meter the VOLTAGE or CURRENT readings seem large and jittery even though the POWER zero may be reading within 1 or 2 digits of 000.

Since by definition RMS values are always positive the meter has been designed so that if the VOLTAGE or CURRENT ranges attempt to go negative then the RMS operation is cancelled and the jitter ceases. This means that with a zero reading of -001 all four functions will read this same value.

In this last case the VOLTAGE and CURRENT readings will still "flash" to indicate that they are below 5 % of their full scale readings.

5-3 CALIBRATION ADJUSTMENT - POWER ZEROS

The Model 258 may be thought of as having a MAIN zero control, P15, a separate "zero" control for each current and voltage range and another zero control for POWER and yet another zero control for POWER X 10. If the MAIN control is left untouched then the POWER X 10 control should not have any influence on the POWER zero however the reverse is not true.

If some component change should cause the MAIN zero control to be adjusted then one must assume that ALL the other zero controls may need adjustment. Because they are "uncoupled" in the Model 258 the POWER control, P127, and the POWER X 10 control, P16, may be adjusted to read 000 whenever desired without changing the setting of other "zero" controls.

Because of the RMS nature of the VOLTAGE and the CURRENT ranges the "zero" controls for these cases are adjusted at (1/20th) of full scale rather than at a true zero input. These adjustments are discussed under the sections on CURRENT and VOLTAGE adjustments.

5-4 PERFORMANCE TESTS - LOW FREQUENCY AC. - VOLTAGE

The performance tests for CURRENT or VOLTAGE can be done in either order. Since the adjustments for the two functions DO have two common controls, P 66, and P 74 it is usually desirable to adjust one function completely and then to "match" the other one to it. Since it usually easier to measure the voltage we consider the VOLTAGE to be the basic FUNCTION. Within the VOLTAGE function the lowest range is considered as the primary range. For illustrative purposes we shall assume that this range is a 20.00 V range. If your instrument has different voltage scales please make the necessary mental adjustments. The other two voltage ranges have separate "ZERO" and FULL SCALE adjustments. The full scale adjustments for the other ranges are made AFTER the lowest (20 V) range has been adjusted, hence they are normally checked after the 20 V range has been shown to be correct.

THE PERFORMANCE TESTS SHOULD BE DONE FOR BOTH CURRENT AND VOLTAGE BEFORE ANY ADJUSTMENTS ARE MADE TO EITHER FUNCTION.

Unless detailed linearity data is required it is usually adequate to check the accuracy and linearity of the VOLTAGE at the three levels of 1/10, 1, and 1.7 times full scale. On the 20 V range this means at levels of 2.00, 20.00 and 34.00 V. This initial accuracy check is normally made at some convenient frequency such as 10 kHz or 50 kHz.(While the tables below indicate the limits of the specifications one really expects considerably better performance. With a sine wave input the VOLTAGE ranges of a correctly adjusted Model 258 are normally expected to be linear within ±5 digits from 1/10th to twice the nominal full scale value of the range.)

INPUT VOLTAGE	ALLOWABLE READING (5000 digit Full Scale
2.00 V	4.77 - 5.27
20.00 V	49.50 - 50.50
34.00 V	84.33 - 85.67

To check the linearity, rather than the frequency response, one should compare the relative values of the 2 V and the 34 V readings to the 20 V reading rather than dealing in absolute values. In an well functioning Model 258 these two readings should each be well within 5 digits of the "proper" relative value. That is if the 20 volt reading is 5010 digits then the 2 V reading should be between 496 and 506 digits while the 34 V reading should be between 8512 and 8522 digits.

If the 20 V range checks out then, if desired, the linearity test may be repeated for the 100 V and the 200 V ranges. The 200 V relative voltage levels are just ten times those for the 20 V range. The absolute limits for the 100 V range are listed below.

INPUT VOLTAGE	ALLOWABLE READING (5000 digit Full Scale
10.0 V	47.7 - 52.7
100.0 V	495.0 - 50.50
170.0 V	843.3 - 856.7

5-5. CALIBRATION ADJUSTMENTS - AC - VOLTAGE (LOW FREQUENCY)

Before making any calibration adjustments it is wise to make sure that thêy are REALLY necessary. One way to convince oneself of this is to check various ranges and functions at various frequencies before adjusting anything.

CHECK THE PERFORMANCE OF THE CURRENT RANGES BEFORE ADJUSTING THE VOLTAGE !

If only one of the higher two VOLTAGE ranges is in error then they have separate FULL SCALE adjustments P 138 and P 140 that are located in the VOLTAGE BOX. These are single turn potentiometers that may be reached through holes in the lid of the VOLTAGE BOX once the bottom cover is removed from the Model 258. Each of these ranges also has its own "ZERO" or 1/20th of FULL SCALE control, P124 and P125.(On the Main board, front left corner)

If the 20 V (or the lowest voltage range in cases where this is NOT 20.00 V) range is in error then one has FOUR controls to consider. These are P 123 the individual range "zero" control, P 74 the 1/10th full scale VOLTAGE and CURRENT control, P1 the VOLTAGE channel gain control, and P 66 the FULL SCALE control for VOLTAGE and CURRENT. If the main ZERO control,P15, is NOT disturbed, then the "zero" or (1/20th) of full scale controls may be adjusted separately for each range.

Before making any adjustments of P1 or P66 one should determine whether BOTH the VOLTAGE and the CURRENT full scale values are in error. If both require adjustment in the same direction (Ageing of some component in the square root circuit might cause this effect.) then P66 should be adjusted. If only the VOLTAGE channel requires a change then P1 should be used. Adjusting P1 will change the POWER gain, while adjusting P66 will NOT change the POWER gain.

The controls for the 20 V range have some interaction hence if a complete recalibration is necessary one must go through the procedure twice to see if any touch up is necessary. (After a full scale input has been applied one should give the instrument several minutes to settle before making any adjustments of the 1/20th of full scale value.)

A. Apply a 1.000 V input (1/20th of FULL SCALE) and adjust P 123 for a an average reading of 250 digits (out of 5000 digits) . The display will flash and may have one or two digits of "jitter" since one is reading "off scale".

B. Apply a 2.000 V input (1/10th of FULL SCALE) and adjust P 74 for a reading of 500 digits (out of 5000 digits). Once P 74 has been adjusted on this range it must be left alone during subsequent range adjustments. The downscale values of other ranges can be adjusted at either 1/10th or at 1/20th of full scale with their individual "zero" control potentiometers

C. Apply a 20.000 V input (FULL SCALE) and adjust P 66 (or P1)for a reading of 5000 digits. P 66 controls the FULL SCALE reading of both CURRENT and VOLTAGE while P 1 controls the FULL SCALE reading of VOLTAGE alone and P 11 controls the FULL SCALE reading of CURRENT alone. (Of course if P 66 has been adjusted in the VOLTAGE case it must NOT be readjusted if CURRENT calibration is also necessary.) Repeat steps A.-C. to see if any readjustment is necessary. (P58 is an overall gain control that may also be used for a slight adjustment of both current, voltage, and power). Allow ADEQUATE settling time when returning to the 1 V level after the 20 V measurements. !

D. Apply a 34.000 V input (1.7 times FULL SCALE) and note that the reading is well within the performance test limits of paragraph 5-4.

5-6 PERFORMANCE TESTS - CURRENT AND CURRENT TRANSFORMERS

For these tests one must consider the transformer/meter combination as a whole. There are two CURRENT inputs, A and B. These two inputs may operate with two different transformers or with different primary windings around or through the primary of the same transformer. Each input is further divided into an A and 5A or a B and 5B range.

From the information in Chapter III, one can see that the actual measurement frequency should be at least 31 times the -3dB break frequency for the transformer in question to reduce the extra amplitude error from the transformer to below 0.05%. With the CT-411 transformer this minimum frequency would be about 31 Hz. With a transformer such as the Ion Physics CM-100 this minimum test frequency would be 37 kHz, while with the Ion Physics CM-10 transformer the minimum test frequency would be 2 kHz.

If a low frequency current calibrator is all that is available this will pose no problem in examining a instrument equipped with a CT-411 however it will rule out direct current measurements with an Ion Physics CM-100.

5-7 CALIBRATION ADJUSTMENTS - CURRENT - (SINGLE FREQUENCY)

If one assumes that the VOLTAGE ranges have already been adjusted then P66 and P74 MUST NOT BE ADJUSTED AT THIS TIME. There is a separate overall gain control, P11 for the CURRENT ranges and there are individual "ZERO" and FULL SCALE adjustments for each of the four CURRENT inputs. Unless some drastic change has been made P11 should not require adjustment. Each range can have its (1/20th) setting and its full scale setting "trimmed" without causing any interaction with other ranges. Assuming that the measurement frequency is at least 31 times the -3dB break frequency for the current transformer in use one drives in an current of (1/20th) of full scale and sets P126 on the A range for a reading of 250 digits . Then with a full scale current for the same range one adjusts P113 for a display reading of 5000 digits. Both the Gain and the "Zero" adjustment potentiometers are arranged physically in the same order as the CURRENT range buttons on the front panel.(IN THE CASE OF SOME EARLY INSTRUMENTS THE "A" "ZERO" CONTROL IS AT RIGHT ANGLES TO THE OTHER CONTROLS AND TO THEIR FRONT LEFT.) A 5A B 5B
.5A 1A .5A .5A

If large adjustments in the "zeros" are necessary then there may be some interaction between the controls. Repeating the procedure a second time should remove any errors from this source.

To avoid confusing possible frequency and amplitude errors one should adjust all four CURRENT ranges to the same FULL SCALE and 1/20 th FULL SCALE values(in digits).

5-8 PERFORMANCE TEST - RESISTIVE LOAD, SINGLE FREQUENCY,AC - POWER

The POWER performance may be checked against a power calibrator, against another wattmeter, or against a combination of a voltage calibrator and a set of appropriately sized, non-reactive resistors.

In any case one should bear in mind that the Model 258 measures the power as the products of the voltage and current THAT IT SEES. Thus if the voltage terminals measure the generator voltage while the current inputs measure the total current from the generator the POWER reading should be this product.

If a WIDEBAND power calibrator is available it may be used to set appropriate combinations of VOLTAGE and CURRENT. These values should check individually when read upon the Model 258.

The most widely available POWER calibrator consists of a VOLTAGE calibrator and a stable and non-reactive resistor of the appropriate value. For a 20 V / 50 mA combination an appropriate for value for the resistor is in the neighborhood of 400 ohms while for a 10 V / 500 mA combination it would be about 20 ohms, and so forth. The resistor should be of adequate wattage that self heating will not cause resistance changes during the measurement. Three 1200 ohm or four 1600 ohm RN60C metal film resistors should be adequate for the 50 mA case.

If both the Model 258 VOLTAGE and CURRENT are accurate, or if their individual errors are known, then the desired POWER reading FOR A RESISTIVE LOAD consists of the product of the VOLTAGE and CURRENT readings. (If the 5000 digit scales are used then one must use the appropriate conversion factors NOT just multiply the CURRENT and VOLTAGE displays.

If both the CURRENT and the VOLTAGE readings are near 5000 digits then the allowable error in the POWER reading is ±75 digits.(5000 digit full scale.) With a resistive load the actual difference between the POWER reading and the VOLT-AMPERE product should be less than ±10 digits for the near full scale case from the lower limit of the transformer to above 1 Megahertz.

Once the positive POWER case has been examined one can reverse the current transformer direction to examine the negative POWER case. In this case the NEGATIVE lamp should flash and the POWER reading should again be equal to the product of the VOLTAGE and CURRENT readings. The differences between positive and negative inputs are normally less than five digits out of 5000 digits for near full scale operation. (Obviously the POWER zero setting must be near zero if the positive and negative readings are to have the same magnitude.)

Other tests may be run to investigate linearity and/or various combinations of low CURRENT coupled with high VOLTAGE or vice versa. There are no separate linearity adjustments. At a frequency of at least ten times the lower frequency break frequency of the transformer in use - a typical Model 258 should have linearity errors of less than 0.1% of full scale over its whole range of specified inputs or outputs.

5-9 CALIBRATION ADJUSTMENT - LOW FREQUENCY AC - POWER

The POWER reading may be set with P 84. If some component such as IC 17 should ever require replacement then P 58 may be used to provide a small adjustment for VOLTAGE, CURRENT, and POWER without disturbing their relative relationships. If either P1 or P11 are adjusted then P84 will probably require adjustment. A reasonable frequency at which to make this adjustment is 50 kHz, or 100 kHz if that is the top frequency available from the calibrator.

The POWER ZERO control P127 should be adjusted to 000 before the full scale adjustment is made.

5-10 PERFORMANCE TEST - RESISTIVE LOAD, SINGLE FREQUENCY, AC - POWER x 10

The same equipment that was used in Section 5-8 may be used for this test. In this case both the VOLTAGE and the CURRENT should be kept at 40 % or less of their full scale values.

The POWER x 10 readings should be the product of the VOLTAGE and the CURRENT readings. If a value of exactly 0.31623 - that is the reciprocal of the square root of ten - times the input VOLTAGE is used with the same load resistor for the P x 10 case as was used for the POWER case then the POWER x 10 readings in digits should be exactly the same as the POWER reading obtained previously.

The POWER x 10 zero - P16 - adjustment should be checked and if necessary adjusted before this test is performed.

5-11 CALIBRATION ADJUSTMENT - RESISTIVE AC - POWER X 10

If the POWER X 10 value requires adjustment then P 14 is the control. If the POWER x 10 "phase controls" C 25 and C27, should ever require adjustment then P14 may require touching up since there is a slight interaction.

5-12-A PERFORMANCE TESTS - RESISTIVE LOAD, AMPLITUDE VS FREQUENCY

If a broadband voltage calibrator is used in conjunction with a non-reactive resistor then one may check the VOLTAGE,CURRENT, POWER, and POWER-x-10 readings simultaneously.

If the same CURRENT transformer is used for all the CURRENT inputs then one can make a circuit argument concerning the "sameness" between the frequency response of all four of the CURRENT inputs. This is the same idea used in the VOLTAGE case. That is that the only circuit difference between the different CURRENT ranges takes place in a low impedance attenuator section, HENCE ALL FOUR CURRENT RANGES SHOULD HAVE THE SAME FREQUENCY RESPONSE. Once this concept is accepted then one need only investigate the frequency response for one VOLTAGE, one CURRENT, one POWER and one POWER X 10 range.

Before recording data it is normally wise to "scan" the frequency range from 50 Hz to 1500 kHz, or whatever portion of this band is of interest or is available from the existing equipment. REMEMBER THAT THE POWER READING IS ONLY SPECIFIED TO 1000 kHz. If there appear to be undue variations then check for proper connections, check for unwanted ground loops, or for unsuspected reactances. Noting whether the variations are present in VOLTAGE, CURRENT, and POWER (below 1000 kHz) or just in one of them may be useful in understanding the problem. If some other method of measurement is available then use it to see if the difficulty is in the generating or in the measuring equipment.

At this point one might make a Table to record CURRENT,VOLTAGE, and POWER and if the calibrator amplitude is easy to adjust, POWER x 10. A reasonable set of frequencies would be 50 Hz,100Hz, 1,10,50,100,200,300, - - 900,1000,1100,1200,1400,1500, and 1600 kHz.(POWER is only specified to 1000 kHz but it is useful to record it to at least 1200 kHz) One might initially only record the data for the first five frequencies then data for alternate values. One can then fill in whatever extra data appears necessary.

A useful line to include in this Table is one for the calculated value of the Volt-Ampere product. Ideally with a pure resistive load this product should continue to equal the power for all frequencies. A properly adjusted Model 258 running at about the full scale levels in all quantities might reasonable be expected to have the VOLT-AMPERE vs POWER difference remain within ±0.25% of each other from 50 Hz to 1000 kHz

In making these measurements one should take care that the current transformer primary is physically fixed so that it is both reasonably near the center, if it is a single wire, and so that it does not move during the test. At high frequencies some slight changes may occur if the primary is moved around during the test.

5-12-B PERFORMANCE TESTS - REACTIVE LOAD SITUATIONS

Since the amplitude and "phase" controls for the Model 258 interact it is wise to check both the amplitude and the phase data BEFORE attempting to make any adjustments.

Between the various ranges of the Model 258 and the various load combinations that one can imagine there are almost an infinity of possible low power factor or "high Q tests. If the user has a particular set of reactances with KNOWN LOSSES these may be used to set up a performance test.

In the general case our experience indicates that an adequate test for the low power factor case is to use capacitors with a known and low loss coefficient as a nearly zero power factor loads. (Mica or polypropylene capacitors - watch out for steel leads - generally have acceptably low losses) One can then add a known resistor in parallel to add a known power loss. For the 50 mA /20 V combination a 400 pF capacitor will draw full scale current at 1 MHz. Thus this capacitor can be used as a nearly zero power factor load, then it can be used in parallel with a 10 kohm metal film resistor to produce a P.F.=0.04 load, and then it can be used in parallel with a 400 ohm resistor. to produce a P.F.= 0.5 load (As a practical matter many generators or amplifiers have a definite upper limits on the capacitance that they can drive, hence one must check that the capacitive load does not cause either oscillation or unwanted output voltage variations in the calibration equipment.)

The capacitor load should be connected in series with the transformer primary. The load should be connected to the HIGH side of the VOLTAGE while the transformer primary is connected to the VOLTAGE COMmon terminal. With this connection the POWER loss measured by the meter will be the capacitor loss plus the loss reflected through the transformer.

With the CT-411 TRANSFORMER and a ten turn primary the reflected loss term should be less than 20 milliohms. If one adds a further 80 milliohms as the loss from the ten turn primary winding then the power loss from a 50 mA current will be 0.25 mW . A 20 V and 50 mA combination coupled with the 5000 digit scale expansion has a POWER resolution of 0.2 mW hence if the capacitive load were truly lossless then the ideal reading would be +1 digit.

At 1000 kHz one will have 1.000 VA in the load. If the capacitor Q equals 1000 then the capacitor loss will be 1 mW or 0.1% of actual input Volt-Ampere product. In this case this would amount to an additional 5 digits for an overall value of +6 digits. Since a high quality mica or polypropylene capacitor might have a Q value between 500 and perhaps 2500 one might reasonable expect the readings to lie between +3 and + 12 digits if the meter were perfectly adjusted and if the input Volt-Ampere product is held at 1.000 and the input CURRENT is held at 50.0 mA.

If one adds a 1% metal film 10,000 ohm resistor in parallel with the low loss 400 pF capacitor then the POWER reading should INCREASE by V^2/R or exactly 40 milliwatts if the voltage is held at exactly 20 V.(As a practical matter a capacitive load often causes an amplifier's output to RISE with frequency hence one should somehow establish whether one really has a constant voltage output as frequency is varied. With an appropriate correction for voltage changes such a resistive addition to a 400 pF capacitor load for a Model 258 "tracked" within 0.1 mW out to 1000 kHz and within 0.8 mW out to 1400 kHz. The effective Q of this composite load is varying with frequency. At 1000 kHz it is (10,000/400) = 25 while at 500 kHz it is 12.5 .

If one combines the 400 pF low loss capacitor in parallel with a pure resistor of about 400 ohms then one will have a load with a variable power factor that will go from near unity at 100 kHZ to about 45° at 1 MHz. If the calibrator or generator can handle the capacitive load while holding its output voltage constant then ideally the CURRENT and the VOLT-AMPERES should increase linearly with frequency while the POWER remains constant at V^2/R. If the calibrator voltage does not remain constant then one must first take its variations into account before computing V^2/R. For this case the VOLT-AMPERE product will increase from about full scale at 100 kHz to 1.5 times full scale at 1000 kHz. Thus the allowable error will increase from ±75 digits at 100 kHz to ±93 digits at 1000 kHz.

5-13 CALIBRATION ADJUSTMENTS : AMPLITUDE and PHASE vs FREQUENCY

As might be expected there are a number of frequency adjusting controls. The user is normally well advised to approach these controls with caution. THEY SHOULD NOT BE TOUCHED UNLESS ONE IS SURE THAT THEY ARE AT FAULT AND ONE IS SURE THAT THEY HAVE THE NECESSARY EQUIPMENT TO COMPLETE THE JOB.

In addition to the controls that will be outlined there are apt to be various unspecified "tweaking" compensation networks in the vicinity of the CURRENT and VOLTAGE amplifiers and the multiplier. These circuits were factory adjusted and should NOT require adjustment.

Since the controls MAY interact one should consider the complete picture before making any adjustments.

Table 7-6 lists all the frequency controls while Drawing 25815 in Chapter IX indicates their position. C-1 is a VOLTAGE channel amplitude control while C-11 is a corresponding CURRENT channel amplitude control. C-133 in the voltage box provides a second voltage control, however unless the voltage box is disturbed this control should not require adjustment. If it were to be adjusted the correct procedure would be to adjust C-133 to make the 200 kHz value of the VOLTAGE equal to the average of the 1 and 10 kHz values.

If C-11 or C 1 were to be adjusted a normal procedure would be to use them to bring the 1 MHz value into line with the 10 and 100 kHz values. There will be an interaction between the adjustments of C-1 and C-133. Hence if one is adjusted the other may require adjustment. If only C-1 or only C-11 is adjusted this is sure to upset the phase shift between the two channels so read on BEFORE making such an adjustment.

An unmarked variable capacitor may exist between IC-13 and IC-15. If it exists this capacitor will offer a small high frequency phase adjustment without causing appreciable amplitude changes.

C-26 and C-28 offer both amplitude and phase adjustment of VOLTAGE, CURRENT, and POWER while C-25 and C-27 operate only in the POWER x 10 case.

As a general rule if a high frequency "phase" deviation is removed, half with C-26 and half with C-28 then the variation of the amplitude response will be minimal. (C-25 and C-27 for the POWER x 10 case). On the other hand if a 1 MHz amplitude variation is removed half with C-26 and half with C-28 then the variation in the phase response will be minimal.

As an example assume that the POWER reading with a capacitive load is in error at 1000 kHz but that the VOLTAGE and CURRENTS amplitudes are correct. One should record all three values then rotate C-26 to remove half the phase error and then C-28 to remove the other half. Turning C-26 will introduce a variation in both the VOLTAGE and CURRENT amplitudes however an equal movement in C-28 should remove this variation while continuing to reduce the phase error. If only one channel has an amplitude error then either C-1 or C-11 should be used. However before making the amplitude adjustment investigate the low power factor case and record its readings so that its change with the C-1 or C-11 adjustment can be noted.

After the VOLTAGE,CURRENT and POWER cases are all correct then the manipulation of C-25 and C-27 should allow one to correct both the amplitude and phase characteristics for the POWER x 10 case.

5-14 SIMPLIFIED CALIBRATION PROCEDURE.

The following sample calibration procedure is suggested as a means of reducing some of the possible problems in obtaining equipment for the calibration of the Model 258.

If a Fluke Model 5100 B or similar calibrator is available then it may be used directly to check and, if necessary, to set the absolute value for all the VOLTAGE ranges. It is good practice to vary the frequency from such a calibrator to show that the readings and or settings are independent of frequency. The calibrator may also be used to check out the LINEARITY of the VOLTAGE ranges.

The Fluke 5100 B may also be used for the direct checking and/or calibration of the CT-411 transformer in conjunction with the CURRENT inputs. A frequency of 5000 Hz should be used for this purpose. After the LINEARITY is checked one may vary the frequency to determine the low frequency response of the TRANSFORMER/METER combination.

The Fluke 5100 B calibrator can usually supply at least 50 mA from its 19.999 V range. Therefore 19.9999 V from the calibrator and a resistor in the neighborhood of 400 ohms will allow one to obtain readings of CURRENT, VOLTAGE, POWER and P X 10 from 50 Hz to 50 kHz.

If a low loss 16,000 pF capacitor is substituted for the 400 ohm resistor then there will be a capacitive current of about 50 mA which according to the arguments above should lead to a reading of between 3 and 12 digits. (From the specification viewpoint the worst case allowable readings would lie between ±75 digits.

Obviously if a calibration source is available that will supply higher currents and voltages at higher frequencies it should be used instead of the outlined arrangement.

IN MAKING SUCH MEASUREMENTS WITH THE TEN TURN CURRENT TRANSFORMER PRIMARY BE SURE TO PUT THE LOAD IMPEDANCE ON THE "HIGH" SIDE OF THE TRANSFORMERS OR CAPACITIVE COUPLING MAY CAUSE HIGH FREQUENCY ERRORS !

5-15 PERFORMANCE and CALIBRATION - INTERNAL REFERENCE SOURCE

The +10V Reference Supply may be checked at the test point located behind IC 224. When read on a high quality, high input impedance, DC meter the +10 V supply should read within ±10 mV of 10.000 V. The adjustment for this supply, P19, should only be varied in an extreme case since this supply is used as an internal reference source by both the -15V supply and by the A/D conversion circuitry.

If for some reason the control, P19, is reset then it will be NECESSARY to recheck and perhaps to reset all the other gain controls of the V-A-W meter.