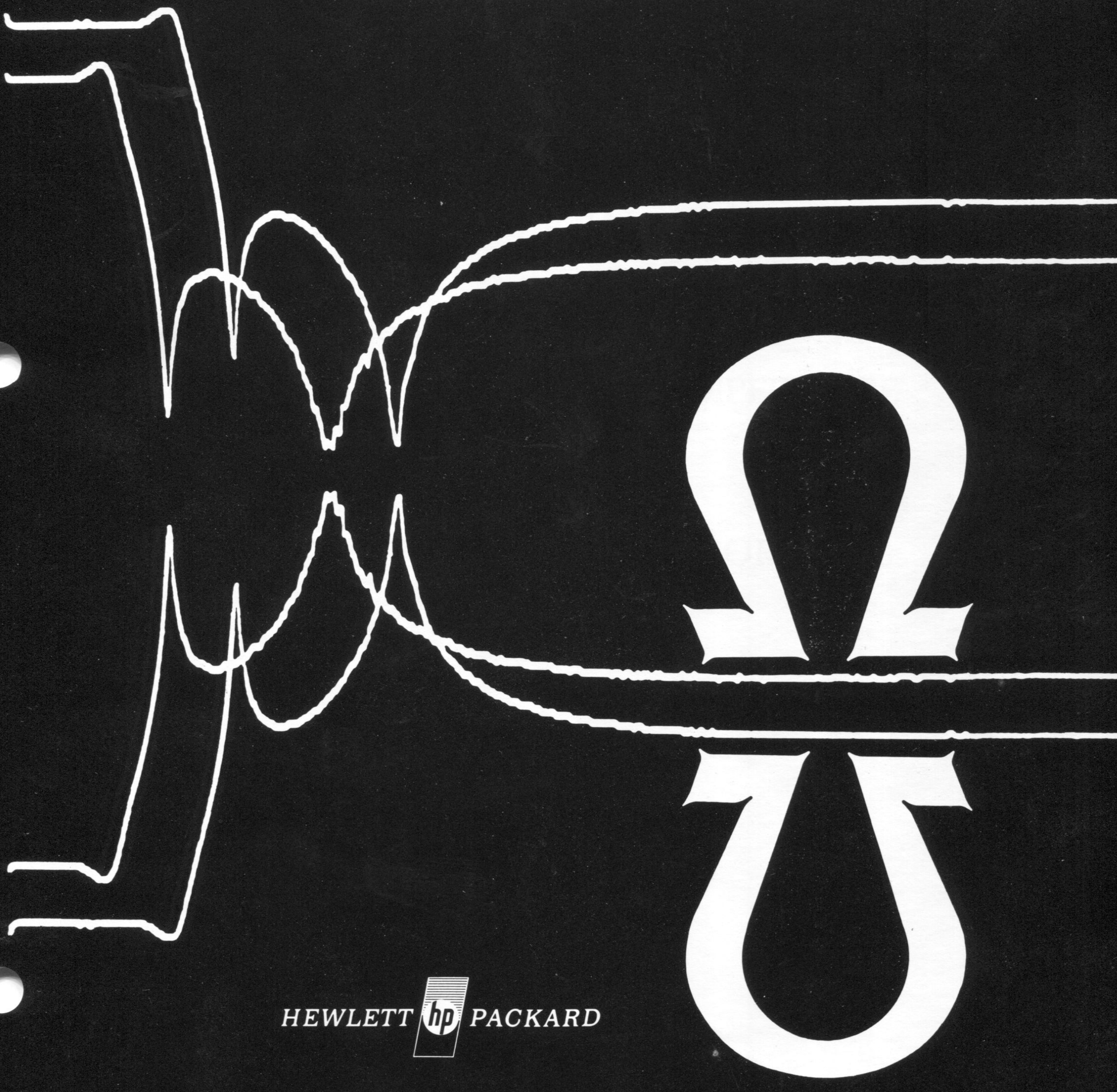
HP AN235

APPLICATION NOTE 235

AN INTRODUCTION TO BALANCED CIRCUITS AND IMPEDANCE MATCHING



HEWLETT hp PACKARD

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SUMMARY

Balanced lines are used quite extensively where wires must be run in a noisy environment. The input is impressed on two wires such that the signal on each wire is 180 degrees out of phase with respect to the other wire. Since most noise is coupled into each line equally, it can easily be separated from the signal. The unwanted signal or noise may be referred to as the common mode signal. Common mode rejection in a balanced circuit is normally referred to as Longitudinal Balance.

Many different methods are used to construct test equipment with balanced input/output ports. The examples in the text indicate some of the more common types of construction. In some cases it is important to understand the internal construction of the test equipment in order to obtain valid measurements. It is also necessary to remember that while many pieces of test equipment with balanced inputs/outputs may be successfully used in the unbalanced configuration, the converse is almost never true.

Impedance matching is normally very important when using balanced instrumentation. Impedance matching devices are available for the more commonly desired conversions and several standard methods exist for changing impedances. The most common methods are matching transformers, balanced attenuator pads, and H typed attenuator pads.

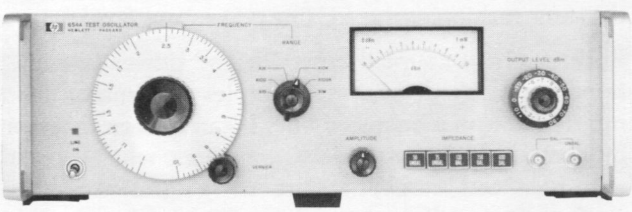
There are several common errors which are made when attempting balanced measurements. One of the most common is the use of unbalanced instruments to make measurements on balanced circuitry. While this procedure may be successful in some cases, it is not recommended. The second most common error is in impedance matching. Mismatches can cause ringing, improper level measurements, and even inconsistent measurements. In many cases even the impedance of the cables used in connecting the test equipment to the circuit under test must be considered.

Balanced circuits and balanced lines are used extensively in the communications' industry. Understanding the applications and use of balanced test equipment is no more difficult than understanding unbalanced equipment. It is, however, important to remember there is a difference, and these differences should be understood before actual measurements are attempted.

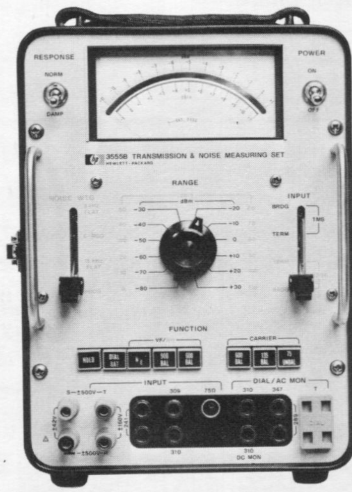
INTRODUCTION

Instruments with balanced terminals, and the use of balanced lines, are fairly common. Many people misuse balanced circuits resulting in improper or misleading measurements. This application note attempts to give a quick overview of the use, and reasons behind balanced circuitry.

An example of misuse is given below. Cases I, III, and IV are giving the correct reading while Case II is incorrect. This will be explained later on.

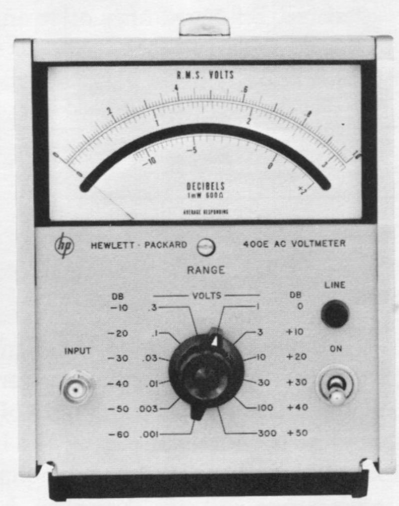


A.
HP Model 654A
600 ohm 0 dBm Balanced Output
Frequency = 1 kHz



C.
HP Model 3555B
600 ohm Balanced Input

B.
HP Model 236A
600 ohm 0 dBm Balanced Output
Frequency = 1 kHz



D.
HP Model 400E
10 M ohm Unbalanced Input

Problem:
Case I: When source A is connected to C the reading is 0 dBm
Case II: When source A is connected to D the reading is 0 dBm
Case III: When source B is connected to C the reading is 0 dBm
Case IV: When source B is connected to D the reading is +6 dBm

BALANCED LINES

DEFINITIONS*

A **balanced line** may be defined as two wires capable of carrying equal signals which are symmetrical about ground and 180 degrees out of phase.

A **balanced circuit** has two terminals carrying equal signals which are symmetrical about some reference point, which is not necessarily ground, where the signals are 180 degrees out of phase.

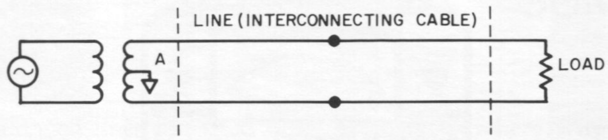


Figure 1.

If point A is considered ground (the symbol shown will represent ground in this application note) the line shown in Figure 1 is said to be a **balanced line.** If point A was not ground, but some other potential, say +5 volts, then the line shown in Figure 1 is not (by definition) a balanced line. The entire hookup is, however, a **balanced circuit.**

REASON FOR USE

Balanced lines are used to reduce the effects of external interference. For instance, telephone lines are often run in close proximity to AC power lines. Power lines create an electromagnetic field which would cause interference (at power line frequency) on an unbalanced line. Shielding against low frequency electromagnetic fields, while possible, is expensive. Balanced lines offer an economical solution to this problem.

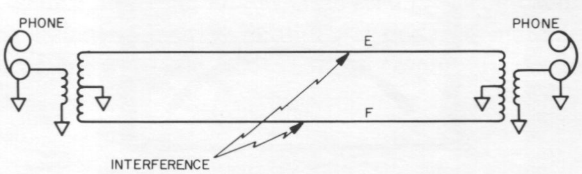
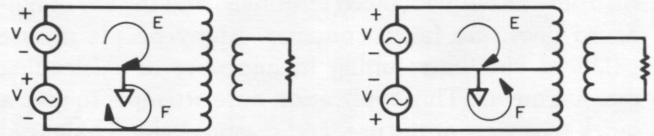


Figure 2.

Figure 2 shows a balanced phone line with interference impinging on the line. If the distance between the lines (E and F) is small relative to the wavelength of the interfering frequency, as is usually the case, the interfering signal is coupled into both lines (E and F) equally and in phase. The interference will not, however, be coupled across either transformer and therefore will be inaudible in the phone. In order for a signal to pass thru the transformer, there must be a 180° difference in phase between the signal from E to ground relative to that from F to ground; see Figure 3.

*The official IEEE definitions for a balanced line and a balanced circuit are given in the appendix.



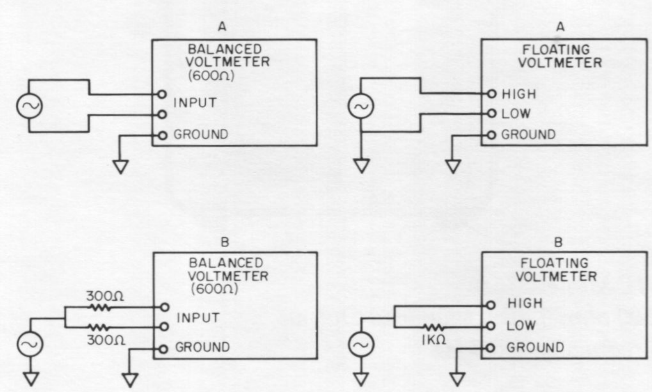
Signal Passed Thru Transformer (Voltage from E to F = 2 V)

Signal Cancelled in Transformer Primary (Voltage from E to F = 0)

Figure 3.

A secondary benefit gained from the use of balanced lines is a significant reduction in crosstalk as compared with unbalanced lines. Crosstalk is, for the most part, coupled into the two lines in phase and therefore doesn't pass thru the transformer coupling. It is cancelled out in the same fashion as the AC line power interference.

Both in phase coupled crosstalk and power line interference are, by definition, examples of common mode interference on a balanced line. It can be seen that common mode rejection is very important when working with balanced lines. There are many different methods used to measure both common mode rejection and longitudinal balance. There is even some disagreement as to their exact definitions; however, measurement of common mode rejection on a balanced line or circuit is called longitudinal balance. Shown below (Figure 4) are the more commonly used methods of measuring both common mode rejection and longitudinal balance on a voltmeter. Although longitudinal balance is normally considered to be a measure of common mode rejection, the fact that a balanced input is being measured requires slightly different techniques. In both cases a reference is first established by connecting the source to the voltmeter in the normal measurement manner (Figure 4-A). The equipment is then connected as shown in Figure 4-B.



Longitudinal Balance

Common Mode Rejection

Figure 4.

Both common mode rejection and longitudinal balance are normally expressed in dB. If the readings in Figure 4-A and 4-B are in volts, then the CMR (common mode rejection) is: CMR = 20 log (V_A/V_B), where V_B is the voltage measured in B (common mode or longitudinal voltage), and V_A is the voltage measured in A (normal mode or metallic voltage). Note that CMR = 20 log (V_A/V_B) = 20 (log V_A - log V_B) = 20 log V_A - 20 log V_B. Thus, if the readings in A and B are taken in dB then CMR = $dB_A - dB_B$.

Example:

V_A = 0 dBV = 1 volt

V_B = -60 dBV = .001 volt

CMR = 20 log (1/.001) = 60 dB

or

CMR = 0 - (-60) = 60 dB

Note that the resistors used to measure Longitudinal Balance must be carefully matched to a tolerance suitable for the level being measured. In the worst case, if the resistors shown were 300Ω±1%, a Longitudinal Balance reading of 30 dB would only be accurate to about ±.4%. Higher Longitudinal Balance readings would have a greater error and vice versa.

Also the value of the resistor used to measure common mode rejection (CMR) as shown is important. Although 1 K ohm is normally used, any value of resistor may be used; the answer obtained will differ. A CMR of 160 dB measured with a 1 K ohm resistor will measure 180 dB if a 100 ohm resistor is used.

LINE IMPEDANCES

Impedance matching is very important. If a circuit impedance is mismatched the power transfer will not be optimum. In cables, standing waves may be created, causing extreme problems. A cable's impedance is a characteristic of the cable and is determined by its internal construction. In communication networks, the following impedances are quite common.

50 Ω unbalanced—used in RF and video coaxial cables

75 Ω unbalanced—used in video coaxial cables

135 Ω balanced—used in the "Basic Group" of Bell Systems communications carrier system in the USA

150 Ω balanced—used in the "Basic Group" of a communication carrier system in Europe

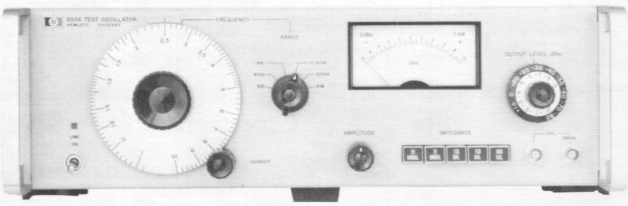
600 Ω balanced—used in cables between central offices of the telephone company

900 Ω balanced—used between the central office and the local telephone in the USA

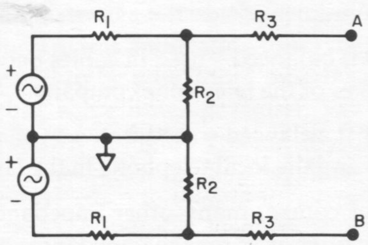
There are, of course, many other impedances and also many, many other uses for the impedances given above. These were given for illustration only. Furthermore, a line's impedance is actually not resistive, although a cable will appear resistive over a fairly wide frequency range, but is a complex network. This network is made up of distributed inductance, capacitance, and resistance, and thus its impedance is frequency dependent. Fortunately, this dependence is slight over a fairly wide frequency range. Cable length MUST, however, be considered if the cable's length approaches the wavelength of the frequency being used. A good rule of thumb is to keep the cable length less than wavelength/360 when possible.

TYPES OF SOURCES AND ANALYZERS

BALANCED SOURCES



HP Model 654A
TEST OSCILLATOR

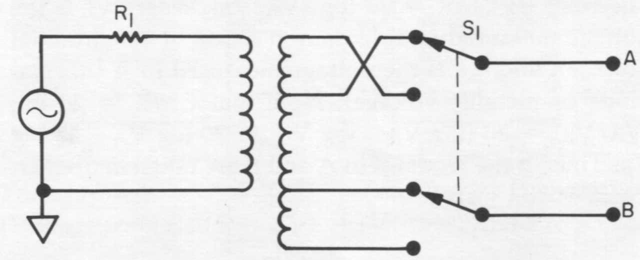


SIMPLIFIED OUTPUT CIRCUIT

Figure 5.

In Figure 5, the values of R_1, R_2, and R_3 determine the output impedance. Note that the circuit is perfectly symmetrical. Also the output at "A" is exactly equal to that at "B" except for a 180° phase inversion relative to ground. The impedance seen between "A" and "B" is the output impedance. In THIS TYPE of balanced source the output impedance and output voltage from "A" (or "B") to ground is one-half of the normal output.

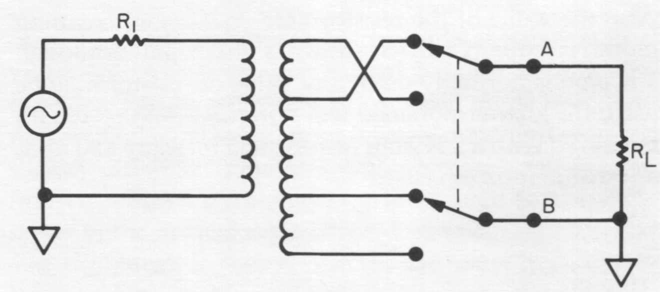
HP Model 236A
TELEPHONE TEST OSCILLATOR



SIMPLIFIED OUTPUT CIRCUIT

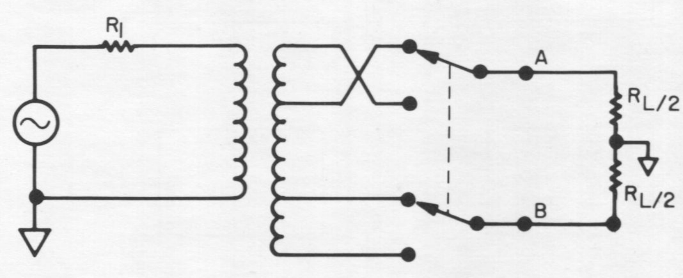
Figure 6-A.

In Figure 6-A, the value of R_1 and the position of S_1 determine the output impedance. Note that there is no ground present at the output. Because of this, the impedance to ground and the voltage to ground (or a reference point) are unspecified. This instrument is not, strictly speaking, a balanced source because of the lack of a reference point. It depends on the external circuit under test to supply the needed reference point. This type of source can be used in either the balanced or unbalanced configuration depending on the external connections (see Figure 6-B and 6-C).



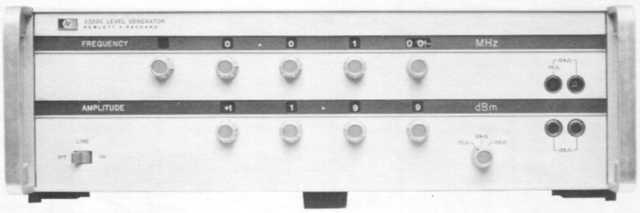
UNBALANCED SOURCE CONFIGURATION

Figure 6-B.

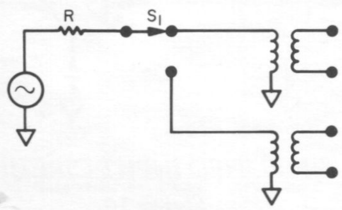


BALANCED SOURCE CONFIGURATION

Figure 6-C.



HP Model 3320C
Frequency Synthesized LEVEL GENERATOR

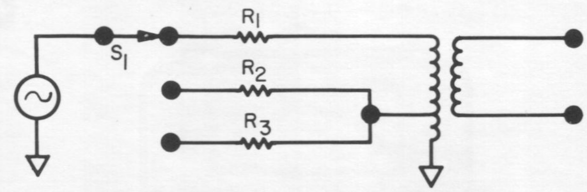


SIMPLIFIED OUTPUT CIRCUIT

Figure 7.

Figure 7 shows a type of source that is very similar to example 2 (Figure 6). The value of R and the position of S_1 determine the output impedance. This circuit also has no ground present in the output and therefore relies on the external circuit to supply a reference point. It can also be used in either the balanced or unbalanced configuration.

HP Model 3551A
TRANSMISSION TEST SET



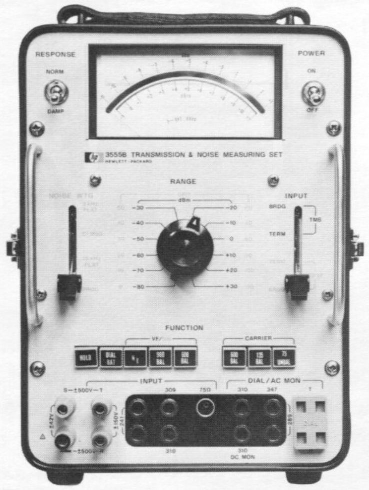
SIMPLIFIED OUTPUT CIRCUIT

Figure 8.

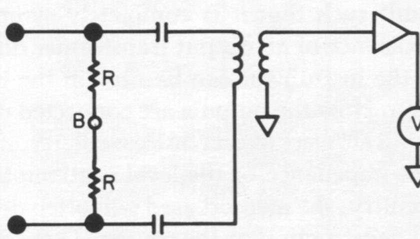
A final example of a balanced source is shown in Figure 8. The position of S_1 and the values of R_1, R_2, and R_3 determine the output impedance. There is again no ground reference in the output (external circuit must supply it) so the output can be used balanced or unbalanced.

All four examples given above have one common factor: they were designed for balanced output operation. Note that an output transformer, when used, must be carefully built such that it is completely symmetrical. The mere existence of an output transformer does NOT insure that the instrument can be used in the balanced configuration. How the outputs are connected may give rise to varying answers as will be shown later. If modification of the impedance or the level is attempted using external circuitry, the method used will often depend on the internal construction of the source. These examples are not the only possible way to obtain a balanced output but represent some of the more typical methods.

BALANCED ANALYZERS

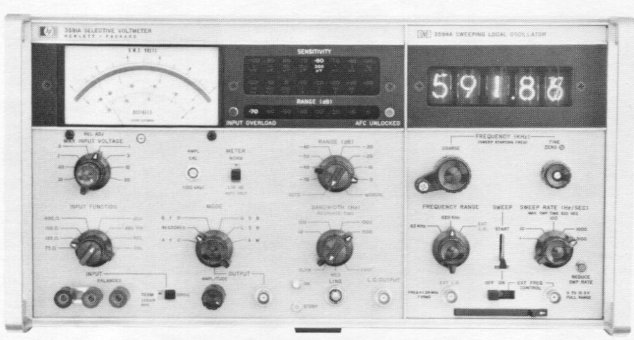


HP Model 3555B
TRANSMISSION & NOISE MEASURING SET

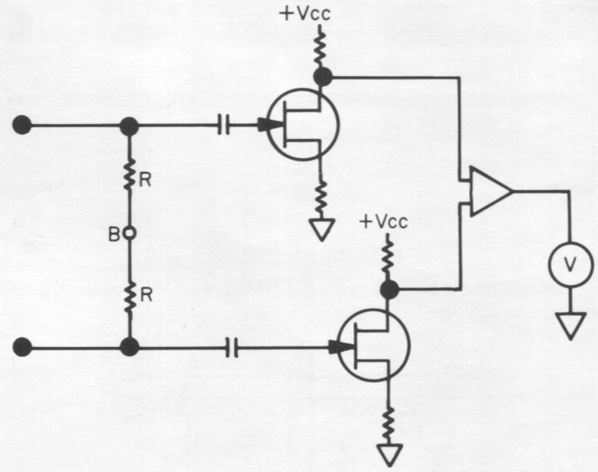


SIMPLIFIED INPUT CIRCUIT
Figure 9.

In Figure 9 the value of the input impedance is determined by R. The R's are normally switched to obtain various input impedances. Note that there is no ground reference on the input side. There is, however, a reference point (B above). This instrument is capable of both balanced and unbalanced operation depending on the external connections.



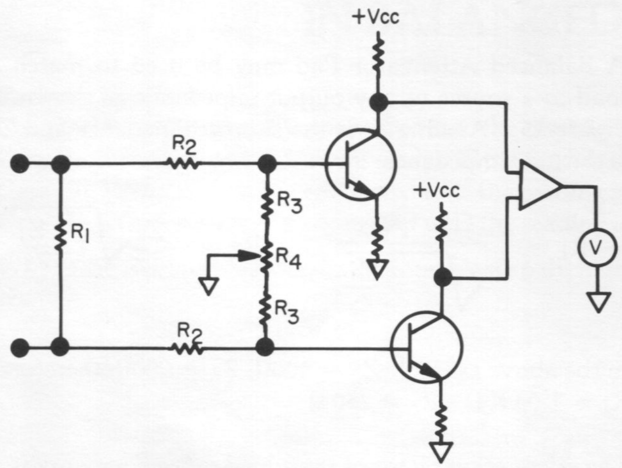
HP Model 3591A
SELECTIVE VOLTMETER



SIMPLIFIED INPUT CIRCUIT
Figure 10.

The circuit in Figure 10 is almost identical to that given in Figure 9. Note, however, that the FETS must be carefully balanced for optimum longitudinal balance. Both balanced and unbalanced operation are possible.

HP Model 3770B
TELEPHONE LINE ANALYZER



SIMPLIFIED INPUT CIRCUIT

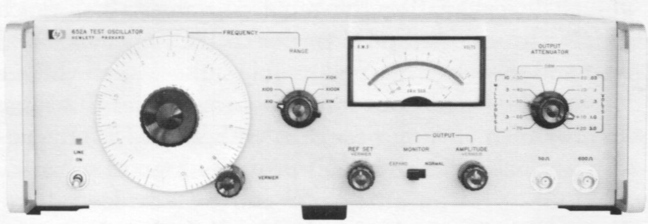
Figure 11.

The value of the input impedance for the circuit shown in Figure 11 is determined by R_1. Resistors R_2 and R_3 are a high value (typically about 30 kΩ) and R_4 is used to compensate for any slight imbalance caused by the transistors (or mismatched resistors). This technique can be used to improve the balance over the analyzer shown in Figure 10; however, it does add a ground reference on the input side. Unbalanced operation should not be attempted with this configuration.

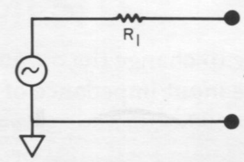
The above examples all have balanced inputs. These are not the only possible methods, but are some of the more typical types.

UNBALANCED SOURCES AND ANALYZERS

For comparison purposes, an unbalanced source and an unbalanced analyzer are illustrated in Figures 12 & 13.



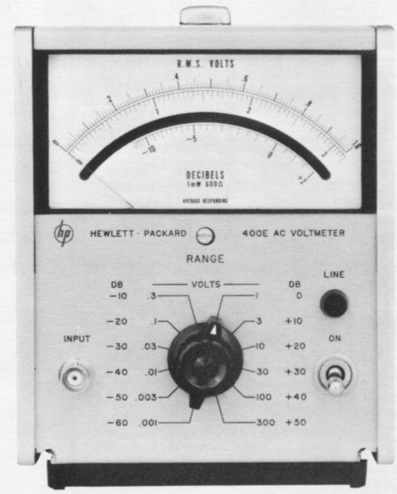
HP Model 652A
TEST OSCILLATOR



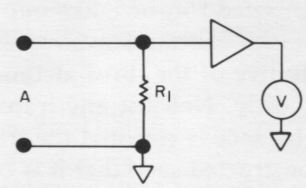
SIMPLIFIED OUTPUT CIRCUIT

Figure 12

The output impedance in Figure 12 is determined by the value of R_1. Typically R_1 is a low value such as 50 ohms. Note that the output A is referenced to ground at all times.



HP Model 400E
AC VOLTMETER



SIMPLIFIED INPUT CIRCUIT

Figure 13.

The input impedance is determined by the value of R_1 in Figure 13. Typically, R_1 is a high value such as 10 M ohms. Note that the input A is referenced to ground at all times.

CHANGING OUTPUT (OR INPUT) IMPEDANCE

It is often desirable to change the output impedance of a given source or the input impedance of an analyzer. For example, if only a 600 ohm source is available for test purposes and a 900 ohm load must be checked. Several methods are shown for changing the output impedance of a source. An analyzer's input impedance may be changed using the same methods.

USE OF A TRANSFORMER

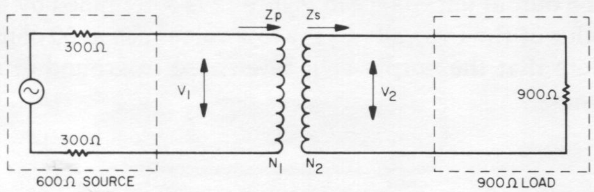


Figure 14.

A transformer has the following properties. If N_1 is the number of turns of wire in the primary and N_2 is the number of turns in the secondary then $V_2 = V_1 \left(\frac{N_2}{N_1}\right)$ (see Figure 14). Also the impedance seen by the source (Z primary) is equal to the secondary impedance (Z secondary) times the square of the turns ratio.

$$Z_p = Z_s \left(\frac{N_1}{N_2}\right)^2$$

In Figure 14 we have $Z_p = 600\ \Omega$, $Z_s = 900\ \Omega$, therefore

$$\frac{N_1}{N_2} = \sqrt{\frac{600}{900}} \approx .82.$$

If a transformer is built using this turns ratio, all the impedances will be matched. Note, however, that the voltages V_1 and V_2 will not be the same. If V_1 equals one volt, V_2 will be about 1.225 volts. The voltage change must be compensated for, or taken into account, when using an impedance matching transformer. This method is the most effective of the three methods given, but is also the most costly. Not just any transformer may be used. If good balance is essential the transformer must be specially constructed such that it is completely symmetrical both internally and with respect to ground (shielding, mounting, etc.). Another problem is bandwidth. Building a balanced transformer which is useable over a wide frequency range is extremely difficult.

BALANCED ATTENUATOR PAD

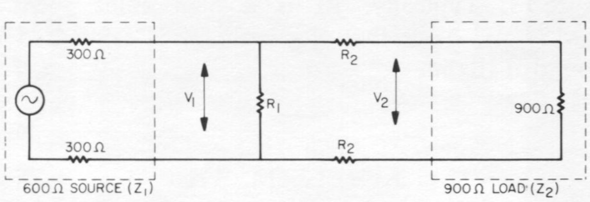


Figure 15.

A Balanced Attenuator Pad may be used to match a load to a source of any output impedance as shown in Figure 15.* Assume Z_1 is the source impedance and Z_2 is the load impedance, then:

$$R_1 = \frac{Z_1}{\sqrt{1 - \frac{Z_1}{Z_2}}} \qquad R_2 = \frac{Z_2}{2}\sqrt{1 - \frac{Z_1}{Z_2}}$$

In the above example $Z_1 = 600\Omega$, $Z_2 = 900\Omega$; therefore, $R_1 \approx 1.04\ K\Omega$ $R_2 \approx 260\ \Omega$

The attenuation factor of the added resistor network is

$$\left(\sqrt{\frac{Z_2}{Z_1}} + \sqrt{\frac{Z_2}{Z_1} - 1}\right)^2$$

or in the above example 3.732. This is equal to a power loss of 10 log 3.732, or 5.72 dB. Notice that although the impedances are now matched, it is still necessary to take the voltage difference into account. This method is inexpensive but is not quite as effective as method 1 due to the impossibility of obtaining exact value resistors with zero tolerance. Also, the resistor R_2 is shown in two places. The degree of balance is very dependent on the availability of resistors which are matched closely in value.

H TYPE ATTENUATOR PAD

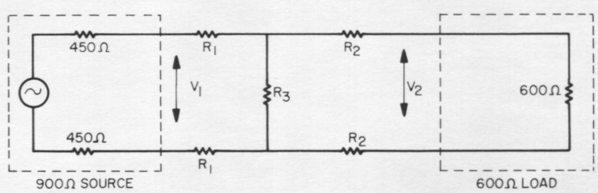


Figure 16.

The H Type pad may also be used to match source and load impedances (see Figure 16).

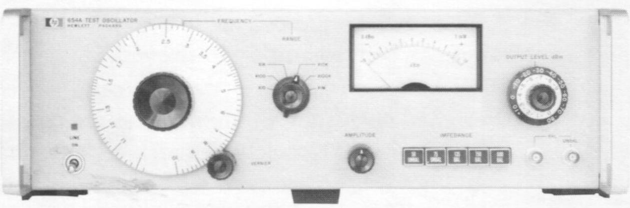
Using this configuration, the attenuation of the network is selectable over a fairly wide range. The disadvantage of an H pad is primarily the length of computation involved in calculating the required values. It is much simpler to use method 2 to match the impedance and then add the necessary pad to obtain the desired voltage level. The H pad does have one advantage; if a large number of matching networks with a known attenuation are needed, the H pad provides a good solution. Method 2 plus an attenuator pad would require nine precision resistors whereas the H pad needs only six precision resistors to accomplish the same result.

*Z_1 is always the smaller of the two impedances (Z_1 and Z_2), no matter whether Z_1 is a source or a load.

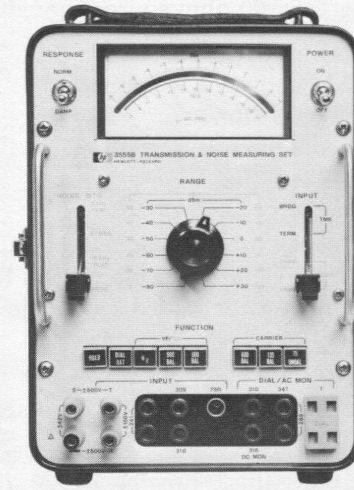
EXAMPLES OF SOME COMMON ERRORS IN BALANCED MEASUREMENTS

Problem (see Figure 17):
Case I: When source A is connected to C the reading is 0 dBm
Case II: When source A is connected to D the reading is 0 dBm
Case III: When source B is connected to C the reading is 0 dBm
Case IV: When source B is connected to D the reading is +6 dBm

Why is the reading obtained in the fourth case 6 dB high?

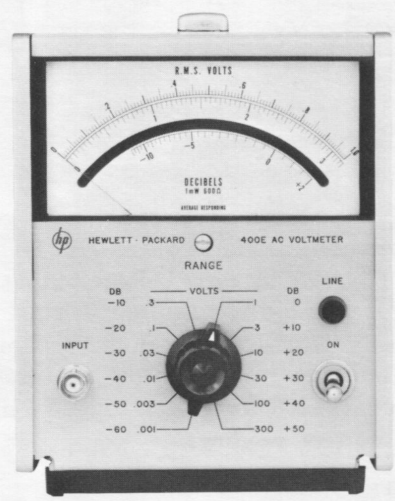


A.
HP Model 654A
600 ohm 0 dBm Balanced Output
Frequency = 1 kHz



C.
HP Model 3555B
600 ohm Balanced Input

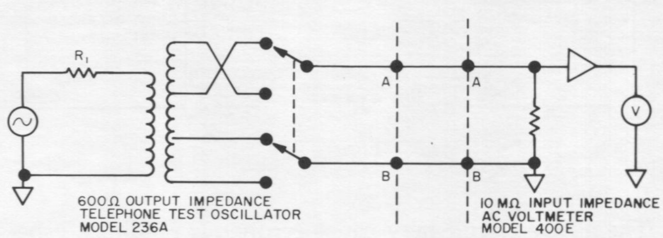
B.
HP Model 236A
600 ohm 0 dBm Balanced Output
Frequency = 1 kHz



D.
HP Model 400E
10 M ohm Unbalanced Input

Figure 17.

Solution:
Note that D is a 400E AC Voltmeter; it has an UNBALANCED input. Also, the input impedance of a 400E is 10 M ohm, not 600 ohms as is instrument C. The reading in Case IV is actually correct with the given configuration. The 400E is reading the "open circuit" voltage from source B (see Figure 18), whereas in Case III the analyzer is reading the voltage across the properly terminated source B. Thus, the reading in Case IV is 6 dB higher than that in Case III. It appears at first glance that a 600 ohm terminating resistor across the input of the 400E would make all readings the same.



IMPROPERLY TERMINATED SOURCE

Figure 18.

If a 600 ohm termination on D, the 400E Voltmeter, is added, the following readings are obtained:

Case I: When source A is connected to C the reading is 0 dBm

Case II: When source A is connected to D the reading is -6 dBm

Case III: When source B is connected to C the reading is 0 dBm

Case IV: When source B is connected to D the reading is 0 dBm

Now Case IV gives proper readings but Case II gives readings 6 dB low. Figure 19 explains this. R_T is the 600 ohm terminating resistor added to enable Case IV to work properly.

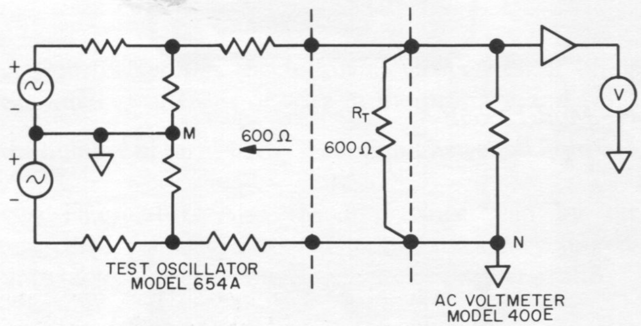


Figure 19.

Note that point M and point N are both ground and therefore common. The unbalanced 400E is shorting out half of the 654A (Source A) voltage output, therefore the reading is now 6 dB low. In the original configuration (Figure 19 with $R_T = \infty$) the ground problem caused the meter to read 6 dB low, and the improper termination (lack of R_T) caused it to read 6 dB high, resulting in a "correct" reading.

Conclusion:
It is important to properly terminate sources and to be very careful of added grounds when using an unbalanced analyzer with a balanced source (or vice versa).

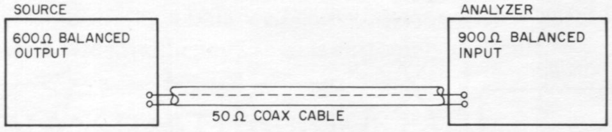


Figure 20.

Problem:
The above circuit may cause erroneous readings, especially at high frequencies.

Solution:
The solution used will not be unique; it will depend on many factors such as frequency, cable length and type, the internal design of the source, and the internal design of the analyzer.

A. If the cable length is short and the frequency low, the circuit may be satisfactory as shown. For better impedance matching add a 150Ω resistor in series with each side of the source output. The analyzer then is driven by approximately a 900Ω source.

B. If a 900Ω or 600Ω balanced cable is available, performance can be measurably improved.
   1. 900Ω balanced cable. If the source is perfect (designed such that all impedances are correct internally) this circuit will work to a reasonably high frequency even with relatively long cables. Adding a 150Ω resistor in series with each side of the source output will increase the maximum usable frequency. If the source is not perfect a matching pad such as that shown on page 9 can be used in place of the 150Ω resistors.
   2. 600Ω balanced cable. The matching problem is now on the analyzer end of the cable. A resistor may be added across the analyzer input such that the cable sees 600 ohms. A 1.8kΩ resistor would be needed in this case (1.8kΩ in parallel with 900Ω ⇒ 600Ω). If the analyzer is not designed such that the correct impedance is seen at the input terminals, use of the matching pad on page 9 should yield some improvement.

C. Coax cables present many problems because standard coax (single conductor with an outer shield) is asymmetrical. In balanced instruments neither output (input) is ground. In Figure 20 the cable shield is being asked to carry the same signal as the center conductor. However, the two signal paths are not symmetrical (capacitance to ground, external fields, etc.) and therefore the inherent balance of the measuring instruments may be seriously degraded. One solution would be using a good 50 ohm unbalanced to 600/900Ω balanced transformer at each end of the cable.

   If this is impossible, then 2 cables of exactly equal length and capacitance can be used, one for each output (input) port. The cable shields can be grounded and both output signals are carried by "identical" paths (center conductors) to their destination. Impedance matching such as discussed in B may provide some improvement also.

Conclusion:

There is oftentimes no best solution. Impedance matching IS important. The degree of importance depends on the application. If flatness is of primary importance then good impedance matching is very necessary. There is, however, a price. Matching pads have loss, sometimes a very large loss. An understanding of the problem should result in better, more accurate measurements.

APPENDIX

1. Definitions per IEEE Std 100-1972

Balanced Line: "A transmission line consisting of two single or two interconnected groups of conductors capable of being operated in such a way that when the voltages of the two groups of conductors at any transverse plane are equal in magnitude and opposite in polarity with respect to ground, the total currents along the two groups of conductors are equal in magnitude and opposite in direction."

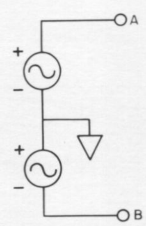
Balanced Circuits: "A circuit, in which two branches are electrically alike and symmetrical with respect to a common reference point, usually ground."

2. Symbols

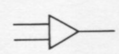
earth ground

ideal AC voltage source (a source with zero internal resistance)

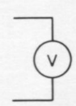
Standard telephone set



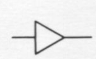
Two ideal AC voltage sources operating 180 degrees out of phase with respect to each other. If the voltage from A to ground is 5 sin θ, the voltage from B to ground is 5 sin $(\theta + 180°) = -5 \sin \theta$.



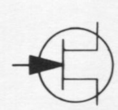
Dual input single ended amplifier, gain unspecified. Inputs must be 180° out of phase to obtain an output.



Voltmeter



Amplifier with infinite input impedances, unspecified gain



N channel Field Effect Transistor (FET)

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