THE DEVELOPMENT OF A GRAPHICAL TECHNIQUE
FOR THE ANALYSIS OF THE PERFORMANCE
OF AN IMPEDANCE BRIDGE

by

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>The Bridge Circuit To Be Analyzed</td>
<td>2</td>
</tr>
<tr>
<td>The Equivalent Bridge Circuit</td>
<td>2</td>
</tr>
<tr>
<td><strong>Analysis Procedure</strong></td>
<td></td>
</tr>
<tr>
<td>Generator Performance</td>
<td>4</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>4</td>
</tr>
<tr>
<td>Output Impedance</td>
<td>7</td>
</tr>
<tr>
<td>Bridge Transfer Function</td>
<td>7</td>
</tr>
<tr>
<td>Bridge Output Voltage</td>
<td>7</td>
</tr>
<tr>
<td>Bridge Unbalance</td>
<td>12</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>17</td>
</tr>
<tr>
<td>Bridge Equivalent Generator</td>
<td>17</td>
</tr>
<tr>
<td>Bridge Performance</td>
<td>17</td>
</tr>
<tr>
<td>Bridge Sensitivity</td>
<td>17</td>
</tr>
<tr>
<td><strong>A Specific Example</strong></td>
<td></td>
</tr>
<tr>
<td>The Bridge Circuit</td>
<td>18</td>
</tr>
<tr>
<td>Generator</td>
<td>18</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>22</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>24</td>
</tr>
<tr>
<td>Inductance Transfer Function</td>
<td>27</td>
</tr>
<tr>
<td>Dissipation Factor Transfer Function</td>
<td>27</td>
</tr>
<tr>
<td>Output Impedance</td>
<td>29</td>
</tr>
<tr>
<td>Bridge Performance</td>
<td>29</td>
</tr>
<tr>
<td>Detector Performance</td>
<td>29</td>
</tr>
<tr>
<td>Sensitivity Curves</td>
<td>32</td>
</tr>
<tr>
<td><strong>Conclusion</strong></td>
<td>34</td>
</tr>
<tr>
<td><strong>Literature Cited</strong></td>
<td>35</td>
</tr>
</tbody>
</table>
TABLE OF FIGURES

1. Impedance Bridge Circuit ........................................... 3
2. Equivalent Circuit of Impedance Bridge .......................... 3
3. Program for Finding Bridge Performance and Sensitivity ...... 5
4. Generator Performance ............................................... 6
5. Circuit for Calculating Input Impedance .......................... 8
6. Circuit for Calculating Output Impedance ........................ 8
7. Circuit for Finding Transfer Function ............................. 10
8. \(|Z_G| = |Z_D|\) .......................................................... 10
9. Values of \(|G|\) for \(|F| = 1\) .......................................... 12
10. \(|G|\) vs \(|F|\) .......................................................... 13
11. Detector Performance .................................................. 16
12. Inductance Bridge Circuit .......................................... 19
13. Bridge Components .................................................... 20
14. Measured Generator Performance .................................... 21
15. Generator Output to a Load .......................................... 23
16. Bridge Input Impedance .............................................. 25
17. Input and Output Voltages ........................................... 26
18. Transfer Function ..................................................... 28
19. Bridge Output Impedance ............................................. 30
20. Bridge Performance ................................................... 31
21. Bridge Sensitivity .................................................... 33
INTRODUCTION

The use of graphical techniques for analyzing bridge sensitivity provides a practical, analytical tool for the design of bridge circuits. Separation of the bridge, generator and detector performances gives the design engineer data in a form that helps with the design of all three circuits.

Bridge sensitivity has been a major design problem ever since impedance bridges were invented. Bridge sensitivity is a function of generator voltage and impedance, the bridge circuit, and the detector impedance and sensitivity. Knowing all these things, you can write an equation for the detector voltage as a function of the bridge unbalance. This is a three mesh equation with six impedances. For a specific bridge setting the solution of such an equation, even with complex impedances, is tedious but by no means impossible. Calculations of this type become impractical, however, when bridge sensitivity must be analyzed for a large number of examples. The analysis of a bridge designed for measuring many decades of impedance value presents a formidable computation problem.

By considering separately, the bridge, the generator and the detector and by employing graphical analysis techniques the labor of these calculations can be greatly reduced. Graphical accuracy is usually sufficient for sensitivity calculations of even the most precision bridges. A graphical technique of this type has already been worked out for resistance bridges (2, p.1-8) and it is now expanded
to show the performance of bridges which include reactive elements.

The Bridge Circuit To Be Analyzed. The impedance bridge consists of four impedances connected in series as shown in Figure 1 with a generator across one pair of opposite corners and a detector across the other pair.

The Equivalent Bridge Circuit. For the purpose of our graphical analysis, however, we will use the equivalent circuit of Figure 2. Here the generator looks into the bridge input impedance which remains relatively constant for even fairly large changes in individual impedance elements of the bridge. The bridge circuit is represented by a transfer function which relates the voltage at its output terminals to the voltage at its input terminals. This transfer function can be considered to be directly proportional to the unbalance of the bridge with a high degree of accuracy for small amounts of unbalance. The detector looks back at a Thévenin equivalent generator whose open circuit voltage is given by the bridge input voltage and transfer function and whose equivalent impedance is the impedance of the bridge circuit looking into its detector terminals. This output impedance is also relatively independent of small changes of individual bridge components and is not materially changed by the impedance of the generator for small amounts of unbalance.
FIGURE 1. IMPEDANCE BRIDGE CIRCUIT

FIGURE 2. EQUIVALENT CIRCUIT OF IMPEDANCE BRIDGE
ANALYSIS PROCEDURE

The details of the bridge analysis are outlined in the flow chart of Figure 3. A discussion of the individual steps will reveal the details of the analysis technique.

**Generator Performance.** To determine generator performance we can plot the generator output voltage as a function of load impedance. If this plot is made as shown in Figure 4 it will be equally useful for finding the voltage and the current into a given load impedance. If the generator and load impedances are similar in magnitude the impedance angular difference between them can have a large effect on the output voltage. We can draw graphs for the generator response for sample impedance angle differences. Looking at Figure 4 you note that there is very little difference between the output voltage for no angular difference and for a load impedance whose angle is ninety degrees different from generator impedance. In practical bridge circuits, we seldom encounter impedance differences much greater than ninety degrees. If larger differences are encountered, it may be necessary to make additional calculations in the range where the impedance magnitudes are comparable. The angle difference has little effect when the impedance magnitude ratio exceeds ten to one.

**Input Impedance.** Referring back to Figure 1 we can consider that the detector is disconnected and that the bridge is balanced. At balance the detector impedance has no effect on the input impedance. Then the input impedance is equal to $Z_A + Z_D$ in parallel with
FIGURE 3. PROGRAM FOR FINDING BRIDGE PERFORMANCE AND SENSITIVITY
FIGURE 4. GENERATOR PERFORMANCE
Z_B \cdot Z_C as shown in Figure 5. This impedance will change with both
the magnitude and angle of the unknown impedance. We can choose a
range of impedance and angle of our unknown and plot the input as a
function of unknown reactance for the extreme values of unknown im-
pedance angle. This gives the input impedance range that the bridge
will present to the generator for any unknown reactance being
measured.

**Output Impedance.** The output impedance is found by consider-
ing the generator in Figure 1 to be disconnected and measuring the
bridge impedance at the detector terminals for the balance condi-
tion. The resulting circuit is shown in Figure 6. This is equal
to Z_A \cdot Z_B in parallel with Z_D \cdot Z_C. Z_{out} is also a function of
both the magnitude and angle of the unknown impedance and is plotted
in a similar manner to Z_{in}.

**Bridge Transfer Function.** The bridge transfer function is
defined as the ratio of bridge open circuit output voltage to bridge
terminal input voltage for a given amount of bridge unbalance.

**Bridge Output Voltage.** When any of the four bridge arms is
unbalanced by an amount \( \Delta \) in proportional parts a predictable open
circuit voltage will appear across the detector terminals.

A balanced bridge has no output voltage. To obtain an output
we need to unbalance the bridge. We want to know how the output
voltage is related to the amount of unbalance.

To determine the output voltage for a component change of \( \Delta \)
proportional parts we can think of the bridge as a pair of voltage
dividers as shown in Figure 7. The impedance ratio of Z_A to Z_D
FIGURE 5. CIRCUIT FOR CALCULATING INPUT IMPEDANCE

![Input Impedance Circuit](image)

FIGURE 6. CIRCUIT FOR CALCULATING OUTPUT IMPEDANCE

![Output Impedance Circuit](image)
remains constant. The ratio of $Z_B$ to $Z_C$ is the same as that of $Z_A$ to $Z_D$ so that there is no output voltage when $\Delta$ is zero. When $\Delta$ is not zero we can calculate the open circuit output voltage from the balance equation (1) and the circuit equation (2).

**Balance equation**

$$\frac{Z_A}{Z_B} = \frac{Z_C}{Z_D}$$  \(1\)

**Circuit equation**

$$\frac{E_{out}}{E_{in}} = \frac{Z_C}{Z_B(1 + \Delta) + Z_C} - \frac{Z_A}{Z_A + Z_D}$$  \(2\)

Since

$$\frac{Z_A}{Z_A + Z_D} = \frac{Z_C}{Z_B + Z_C}$$  \(3\)

We have

$$\frac{E_{out}}{E_{in}} = \frac{Z_C}{Z_B(1 + \Delta) + Z_C} - \frac{Z_C}{Z_B + Z_C}$$  \(4\)

Which gives

$$\frac{E_{out}}{E_{in}} = \frac{Z_B Z_C \Delta}{Z_B + Z_C \left[ 1 + \frac{Z_B \Delta}{Z_B + Z_C} \right]}$$  \(5\)

Or

$$\frac{E_{out}}{E_{in}} = \frac{Z_B \Delta}{Z_C \left[ 1 + \frac{Z_B^2}{Z_C \left( 1 + \frac{Z_B}{Z_C} \frac{\Delta Z_B}{Z_C} \right)} \right]}$$  \(6\)

To determine the voltage $E_{out}$ which will be supplied to the detector for a small amount of bridge unbalance we can assume that the bridge input voltage $E_{in}$ remains constant. In proportional
FIGURE 7. CIRCUIT FOR FINDING TRANSFER FUNCTION

\[ |Z_C| = |Z_D| \]
parts the input will usually change less than \( \Delta \), the amount of the unbalance. This may not be true if all of the components are reactance elements and the system is operating very near resonance. This is an improbable case. If it occurs additional calculation may be necessary. For most generators and bridge circuits the resistive elements will produce enough dissipation so that the input voltage variation will never exceed a few times the impedance change in proportional parts. We can obtain a graphical relation between the bridge transfer function, \( G \), and the arm impedance ratio, \( F \), easily if we make a few assumptions.

If \( \Delta \) is small compared to one, as it usually will be, we have a simpler expression for \( G \).

For \( \Delta \ll 1 \)

\[
G = \frac{F}{(1 + F)^2 \left( \frac{1 + F}{1 + \frac{1}{F}} \right)} = \frac{F}{(1 + F)^2}
\]  

(7)

where

\[ G = \frac{E_{\text{out}}}{E_{\text{in}} \Delta} \]  

(8)

and

\[ F = \frac{Z_B}{Z_C} \]  

(9)

\( F \) and \( G \) are vector quantities which can have any magnitude or angle. Usually we are not greatly interested in the angle of \( G \), only its magnitude. The angle of \( F \), however, can have a profound influence if the magnitude of \( F \) is near one. This case is shown graphically in Figure 8. If the magnitude of \( F \) equals one, that is, the two impedances of one of the dividers have equal magnitudes, we can find
the values of $|G|$ as a function of the angle of $F$. From Figure 8 we can see that

$$1 + F^2 = \sin^2 F + (1 + \cos F)^2$$

(10)

$$= \sin^2 F + 1 + 2\cos F + \cos^2 F$$

(11)

$$= 2(1 + \cos F)$$

(12)

so

$$G(|F| = 1) = \frac{1}{2(1 + \cos F)}$$

(13)

If the two impedances have the same angle then $\angle F$ equals zero and $G = 0.25$. If one is a capacitor and the other an inductor of equal impedance then $\angle F$ equals $180^\circ$ and $|G| = \infty$. Any angle from $-180^\circ$ to $+180^\circ$ is possible. Some resulting values of transfer function, $G$, for different impedance angle differences are shown in Figure 9.

| $\angle F$ | $|G|$  |
|------------|-------|
| 0          | 0.25  |
| $90^\circ$ | 0.5   |
| $170^\circ$| 32.8  |
| $180^\circ$| $\infty$ |

**FIGURE 9. VALUES OF $|G|$ FOR $|F| = 1$**

If the two impedances have different magnitudes the angle variation has less effect. A plot of $|G|$ versus $|F|$ for several values $\angle F$ is given in Figure 10. Since both bridge impedance pairs are in the same ratio and this plot is symmetrical on log-log paper, it follows that we will get the same output voltage for a change $\triangle$ in proportional parts of any of the four impedances of the bridge.

**Bridge Unbalance.** The bridge unbalance can be given as a
FIGURE 10. $|G|$ vs $|F|$
proportional difference or as an impedance difference. For example, if the bridge accuracy is given as $\mp(\% + \beta$ dial divisions) the calculation can be made for $\alpha\%$ or for $\beta$ dial divisions or both. To make the calculation we would first assume that the bridge was balanced, then change the unknown impedance $Z_u$, by an amount $\Delta$ in proportional parts such that $Z_u$ would become $Z_u(1 + \Delta)$. $Z_u$ can be represented in either rectangular or polar co-ordinates:

$$Z_u = R_u + jX_u$$  \hspace{1cm} (14)

or

$$Z_u = |Z_u| \cos \theta$$  \hspace{1cm} (15)

Typically in bridge circuits we change only one component at a time. For example, we could change inductance (by $\Delta_L$) then we would have

$$Z_u(1 + \Delta) = R_u + jX_u(1 + \Delta_L)$$  \hspace{1cm} (16)

or

$$Z_u(1 + \Delta) = (R_u + jX_u) \left(1 + \frac{\Delta_L}{1 + \frac{R_u}{jX_u}}\right)$$  \hspace{1cm} (17)

where

$$X_u = \frac{\omega L}{1 + \frac{R_u}{jX_u}} = \frac{j\omega L}{1 - jD}$$  \hspace{1cm} (18)

so

$$|\Delta| = \frac{\Delta L}{\sqrt{1 + D^2}}$$  \hspace{1cm} (19)

where

$$D = \text{dissipation factor} = \cot L$$
If this bridge had a resistive arm calibrated in inductance value a change of $\Delta$ in its value would produce the same effect as a change of $\Delta$ in $Z_u$ but as shown in equation (19) the inductance change that this represents would only change $Z_u$ by $\Delta/\sqrt{2}$. Changing $L$ in $Z_u$ also changes $L_u$ which requires that another bridge dial be moved also. Usually we are interested in the bridge sensitivity to bridge dial variations so we will consider only changes of the dials, not of the unknown impedance components.

**Detector Performance.** The bridge output now looks like an equivalent generator with an output voltage and an output impedance, both of which are a function of both the magnitude and angle of the unknown impedance. The detector input impedance looks like a load impedance to this generator. We are going to assume that the detector input remains constant and find out what equivalent generator voltage and impedance are required to give a predetermined detector deflection. The detector curve in Figure 11 is a plot of the voltage and impedance combinations which give this deflection. This detector plot is the key to this particular graphical technique. The ability to analyze the bridge and detector separately makes it a simple process to analyze bridge performance with a large number of different detectors without re-doing the complicated bridge calculations. We have now obtained our fundamental information and can proceed to combine it to obtain the desired plots.

**Input Voltage.** The generator performance curve and the input impedance curve can be used to plot a curve of input voltage versus unknown impedance.
FIGURE II. DETECTOR PERFORMANCE
Output Voltage. The input voltage and bridge transfer data combine to give an output voltage curve. If the bridge has two controls (e.g. inductance and quality factor) we can plot output voltage curves for each.

Bridge Equivalent Generator. The source describing point as shown in Figure 4 can be plotted for all values of unknown impedance. The data for this plot is taken from the output impedance and output voltage curves.

Bridge Performance. If we plot the bridge output voltage and impedance for a given amount of unbalance, $\Delta$, on the detector graph we can see which bridge output conditions will be capable of giving our predetermined detector deflection and which ones will not. By choosing the detector deflection as either the minimum observable signal or the minimum signal which can be detected above the noise level, our combined graph will tell us which ranges of the bridge can be used with the sensitivity indicated by $\Delta$.

Bridge Sensitivity. For small amounts of unbalance the output voltage is almost directly proportional to $\Delta$. As a result, we can find the voltage difference between the bridge and detector curves on the bridge performance graph and plot the bridge sensitivity versus value of the unknown impedance.
A SPECIFIC EXAMPLE

The exact procedure for bridge calculations can only be outlined, because the individual circuits make considerable differences in the techniques for the calculations. The analysis of the inductance bridge shown in Figure 12 will serve to show the details of the calculation. The bridge will also provide an experimental model so that the results can be checked.

The Bridge Circuit. The bridge that we are going to analyze is used for measuring values of inductance and dissipation factor for the equivalent parallel circuit of impedances connected to the unknown terminals. The bridge components are shown in Figure 13. We are going to analyze the circuit for dissipation factor values of zero and one. For higher dissipation factors a series inductance bridge should be used. For all except the lowest range we are going to analyze the circuit for Main Dial DEKASTAT® Decade Rheostat settings from one-tenth full scale to full scale. At lower settings one should go to the next lower range.

Generator. The generator curve was drawn experimentally. The generator was operated at one kilocycle per second. First, a variable resistor, then, a variable capacitor were used as load impedances. From these two sets of measurements the generator output impedance was found. The measured curves are shown in Figure 14. Since the generator internal and load impedances make a voltage divider like that in Figure 7 we can use equation (13) to find the generator impedance from the measurements at 700 ohms where
FIGURE 12. INDUCTANCE BRIDGE CIRCUIT
FIGURE 13. BRIDGE COMPONENTS
FIGURE 14. MEASURED GENERATOR PERFORMANCE
the generator and load impedances have equal magnitudes.

From equation (13)

\[
\frac{\text{Voltage for } |Z_{\text{load}}| = |Z_{\text{gen}}|}{\text{Open Circuit Gen Voltage}} = \frac{1}{2 \cdot [1 + \cos(\angle Z_{\text{load}} - \angle Z_{\text{gen}})]}
\]

Substituting from the data for a capacitive load

\[
\frac{21}{19} = \frac{1}{2 \cdot [1 + \cos(-90^\circ - \angle Z_{\text{gen}})]}
\]

Solving for \( \angle Z_{\text{gen}} \)

\[
\cos(-90^\circ - \angle Z_{\text{gen}}) = \frac{19}{(21)(2)} - 1 = -0.548
\]

\[
-90^\circ - \angle Z_{\text{gen}} = \tan^{-1}(-0.548) = 123.2^\circ
\]

\[
\angle Z_{\text{gen}} = 123.2^\circ - 90^\circ = 33.2^\circ
\]

Solving for \( Z_{\text{gen}} \)

\[
Z_{\text{gen}} = 700 \cos 33.2^\circ + j700 \sin 33.2^\circ
\]

\[
Z_{\text{gen}} = 550 \Omega + j383 \Omega
\]

In Figure 15 we have the generator performance plotted as a function of the input impedance for two conditions. One, when both the generator and load impedances have the same angle and two, when the angles are 90° different.

**Input Impedance.** For our bridge circuit the input impedance equation is

\[
Z_{\text{in}} = \frac{\frac{\omega L_u}{B} + (D_u - j)}{\omega RC + (D_u - j)}
\]

where

- \( R \) is the range resistor in ohms
- \( \omega \) is 2πf in radians per second
FIGURE 15. GENERATOR OUTPUT TO A LOAD
L is the unknown equivalent parallel inductance in henries.

D is the dissipation factor of the unknown impedance in proportional parts.

C is the capacitance of standard capacitor in microfarads.

j is \(\sqrt{-1}\).

For the first range, \(R = 1\Omega\) at dial settings of 1, 3 and 10 times \(10^{-4}\) we get

for \(D = 0\)

\[
Z_{in} = \frac{0.6280}{6.280} \approx 1 + j \frac{0.6280}{6.280}
\]

for \(D = 1\)

\[
Z_{in} = \frac{1.6280}{7.280} \approx 1 + j \frac{1.6280}{7.280}
\]

These are plotted on Figure 16 as are the values for the other ranges. These sample values are enough for the accuracy that we need. The co-ordinates of Figure 16 are impedance angle versus log impedance magnitude with the scales marked in resistance and reactance magnitude (1, p.277-278). Horizontal distances on this plot are log impedance magnitude ratios and vertical distances are impedance angle differences.

**Input Voltage.** By plotting the generator impedance on the input impedance graph we can get the impedance ratios and angle differences that we need to find the input voltage. The resulting values of input voltage are found on Figure 17.
FIGURE 17. INPUT AND OUTPUT VOLTAGES
Inductance Transfer Function. The transfer function, equation (7), will be the same for each range. The equation for the impedance ratio at balance is

\[
F = \frac{\omega LC}{D - j} \left(1 + \frac{\omega LC}{D - j}\right)^2
\]

where

- \(L\) is the resistance of the Main Dial DEKASTAT in kilohms
- \(C\) is the capacitance of the standard capacitor in microfarads
- \(D\) is the dissipation factor in proportional parts
- \(\omega\) is the frequency in kiloradians per second.

Using equation (30) and equation (7) Figure 18 was plotted. The vertical distances on Figure 18 represent the ratio of output to input voltages so a pair of dividers or a light table can be used to produce the output voltage curves on Figure 17. There are two sets of output voltage curves for low inductances. One set is for values of \(\Delta\) of 0.1% unbalance, the other set is for one dial division unbalance.

Dissipation Factor Transfer Function. For the inductance bridge we are usually more interested in the ability of the D dial to resolve small D changes than in the absolute accuracy of D. One dial division on the lowest D range changes D by 0.001 which gives \(\Delta\) a value of 0.1% of a radian for D = 0 and 0.07% of a radian for D = 1. These changes are approximately the same as the 0.1% inductance change already plotted. So our curves give the output
FIGURE 18. TRANSFER FUNCTION
voltage for either one dial division D or 0.1% inductance change.

**Output Impedance.** The output impedance equation can be reduced to

\[ Z_{\text{out}} = \frac{I_u}{C Z_{\text{in}}} \tag{31} \]

The curves of Figure 19 can be easily drawn from the curves of Figure 16 by using a light table. If Figure 16 is rotated 180° about the point \( Z = 1 \) it becomes a plot of \( 1/Z_{\text{in}} \) which can be displaced by the ratio \( I_u/0 \) to give \( Z_{\text{out}} \).

**Bridge Performance.** The data from Figure 17 and Figure 19 are combined on Figure 20 to show the bridge output for \((0.1\% + 1\) dial division) inductance change or for 0.001 dissipation factor change.

**Detector Performance.** A signal source was connected in series, first, with a variable resistor and, then, a variable capacitor and adjusted to give a barely detectable detector deflection. The results were used to analyze the detector input impedance and to generate the detector curve shown in Figure 20. The upper curve indicates minimum sensitivity, when the bridge and detector impedances have the same angle. The lower curve indicates maximum sensitivity, when the bridge output is purely inductive. A similar plot for a set of headphones is also shown. A bridge plot which is vertically above the detector curve indicates satisfactory performance. The bridge plots below the detector curve indicate insufficient sensitivity to show a change as small as the \( \triangle \) that was chosen.
FIGURE 19. BRIDGE OUTPUT IMPEDANCE
FIGURE 20 BRIDGE PERFORMANCE
Sensitivity Curves. Figure 21 shows the sensitivity in percent bridge unbalance for minimum detectable signal. The data for these plots is taken directly from Figure 20. Values of 100 nanohenrys, 2 millihenrys and 800 millihenrys were checked and found to produce the predicted indicator deflection.
FIGURE 21. BRIDGE SENSITIVITY
A graphical technique for bridge evaluation has been presented and used to study the design of an inductance bridge. The bridge performance plot as shown in Figure 20 has many desirable features. It shows the equivalent Thevenin generator parameters for bridge output at a glance; it provides a simple means for evaluating the usefulness of a detector, or the characteristics that should be looked for in a new detector. It permits sensitivity plots to be made rapidly for new detectors without having to repeat the entire bridge analysis. The plot can be changed easily for new generators, too. The ratio of the new input voltage to the old input voltage is the same as the ratio of the new output to the old output voltage. The bridge curves will move vertically by this ratio on the voltage scale. This analysis technique has already proved to be very useful in resistance bridge analysis (2, p.1-8) and it appears that it may be of even greater value in the analysis of impedance bridges.
LITERATURE CITED
