VACUUM TUBE, BRIDGE, AND RESONANCE METHODS OF MEASUREMENT

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VACUUM TUBE, BRIDGE, AND RESONANCE METHODS OF MEASUREMENT

A Basic D.C. Vacuum Tube Voltmeter

MAKING measurements that show how a transmitter is operating is one of the important duties of a radio operator. If he does maintenance work as well, he frequently also finds it necessary to make other kinds of measurements that show him whether some part has failed or is in danger of failing. For these reasons, a communications man needs to know a great deal about measurements.

This Lesson is intended to give you a background for future studies on this important subject. We will start by describing a basic instrument, the vacuum tube voltmeter, that forms a part of many transmitter measuring circuits. Then we will show you how the properties of coils and condensers are measured at audio and radio frequencies by various methods. Finally, we will discuss the subject of measuring frequency. We will not take up at any great length the actual instruments used in making measurements in transmitters, because a later Lesson will be devoted to that important subject. Here we want you to gather fundamental information that will make your future studies easier to understand.

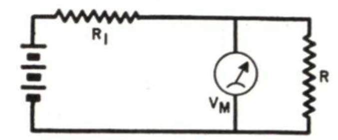

FIG. 1. The measurement depends on the voltmeter current, compared to that drawn by R.

First, let's see what a vacuum tube voltmeter is and why it is often a more useful instrument than the kinds of voltmeters you have already studied.

You recall that ordinary voltmeters affect the circuit whose voltage they measure—because they draw current and because they add the meter resistance to the circuit. Even in a simple circuit like Fig. 1, the voltmeter will not indicate the true voltage across R unless its resistance is many times higher than that of R, because the voltmeter current through R_1 causes an additional voltage drop. As you have learned, the voltmeter ohms-per-volt sensitivity determines the extent of the difference between the voltmeter reading and the actual voltage when the meter is removed.

Nowadays, standard meters have sensitivities of 1000 ohms-per-volt to 25,000 ohms-per-volt. But where very high resistances are used, as they are in so many radio applications, increased voltmeter sensitivity is needed. That's why d.c. vacuum tube voltmeters are used.

BASIC TRIODE V.T.V.M.

Fundamentally, a vacuum tube voltmeter is just an ordinary amplifier stage having an indicator instead of the usual plate load. Fig. 2A shows a typical triode circuit. An E_g-I_p characteristic curve for this type tube is shown in Fig. 2B. By using the proper grid bias, we can operate on the straight part of the characteristic (point 1), over a curved portion (point 2), at cut-off (3), or even beyond plate current cut-off (4), depending upon just what circuit action we want.

Suppose we operate on the straight part of the characteristic, the tube then

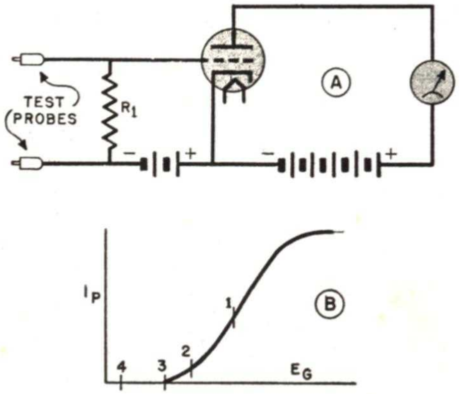

FIG. 2. An ordinary amplifier stage makes an excellent d.c. vacuum tube voltmeter, as the plate current is proportional to grid voltage.

acting as a class A amplifier. There will be a no-signal plate current, indicated by the meter in the plate circuit. We can make the meter read mid-scale for this current by using a shunt resistor across the meter or by adjusting the plate and grid voltages.

Now if we connect the test probes to a d.c. voltage source, current will flow through grid resistor R_1, causing a voltage drop across it. This grid voltage will either increase or decrease the plate current, depending on the polarity of the drop. By calibrating the plate current meter properly, we can use it to measure the voltage of the source that R_1 was connected across, so we have made a simple d.c. vacuum tube voltmeter out of a standard radio tube amplifying circuit.

CIRCUIT LOADING

Why is our vacuum tube voltmeter (or "v.t.v.m.," as radio men call it) any better than an ordinary meter? We put the resistor R_1 across the source of voltage being measured—just as we'd have put the meter resistance across the source if we used an ordinary voltmeter. The difference is the fact that R_1 can be made very large. The only real limits on the size of R_1 are the grid current that may result from contact potential and gas within the tube. If resistor R_1 is too large, these tiny currents would cause a positive voltage drop across it that could nullify the C bias and cause erratic changes in plate current. However, resistor R_1 can be as high as 10 or 15 megohms—far higher than the resistance of any ordinary voltmeter. For this reason, a v.t.v.m. will load the measured circuit much less than will a D'Arsonval meter.

For example, if resistor R_1 is 15 megohms and 3 volts across it will give a full-scale meter deflection, the sensitivity of our v.t.v.m. is 5 megohms-per-volt. Commonly, sensitivities of from 1 to 5 megohms-per-volt are obtained on the basic range in commercial types. This is obviously many times higher

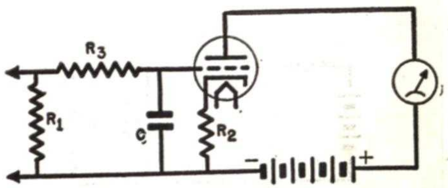

FIG. 3. The filter C-R_3 prevents a.c. ripples from affecting the d.c. voltage readings.

than even the best 25,000 ohms-per-volt D'Arsonval meter.

Of course, the simple circuit shown in Fig. 2 needs improvement. Its amplification, and therefore its calibration, will change if the supply voltages change; the device will be affected by any stray a.c. voltages; it has only one range; and the circuit does not make full use of the meter sensitivity. Let's see how these limitations can be cured.

Minimizing Supply Voltage Effects. Our v.t.v.m. can be improved by putting a self-bias resistor (like R_2 in Fig. 3) in the cathode lead. With this arrangement, if the plate current drops because of tube aging or battery supply reduction, the bias voltage will also drop. This tends to keep the plate current more nearly constant. Since this bias changes with plate current variations caused by the applied voltage, the bias tends to oppose the applied voltage. The tube is forced to act as if it had a lower amplification factor, but the stage characteristics are made relatively independent of the tube and supply voltages. This method (called degeneration) sacrifices some sensitivity, but the benefits outweigh the loss.

Keeping Out A.C. Since the circuit in Fig. 2 is an amplifier, any a.c. voltage applied across resistor R_1 will cause an a.c. variation of the plate current. This will not affect the D'Arsonval meter, which indicates only the average d.c. plate current. However, if this a.c. exceeds the bias, the grid will swing positive and grid current will flow, causing false readings.

Fig. 3 shows how a.c. trouble can be avoided. Here, resistor R_3 and condenser C in the grid circuit act as an a.c. filter. The applied a.c. is dropped across R_3, because its resistance is large compared to the low reactance of C. This reduces the level of any a.c. input voltages at the grid of the tube. Should these voltages still be high enough to swing the grid positive, R_1-R_3-C act as a grid leak and condenser, automatically biasing the tube. This scheme lets us measure the d.c. voltage in a circuit containing both a.c. and d.c., without having the a.c. affect the reading.

Extending the Range. Since we might want our v.t.v.m. to measure d.c. voltages ranging from just a fraction of a volt to 1000 volts or more, we need some means of extending the meter range. A good circuit for this purpose is shown in Fig. 4. When the selector switch is in position 1, resistors R_1, R_2 and R_3 are all across the grid-cathode of the tube, and all the input

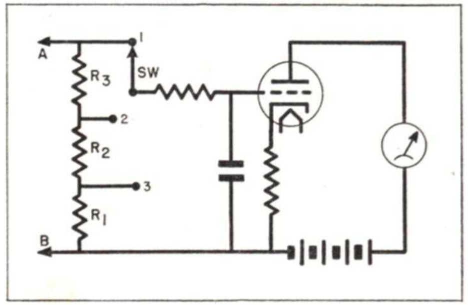

FIG. 4. A voltage divider method of extending the range.

voltage is fed into our v.t.v.m. Switch position 1, therefore, sets the meter to its basic range.

When the selector switch is moved to position 2, only part of the input voltage is applied to the input of the v.t.v.m., because the circuit acts as a voltage divider. The exact amount of division depends upon the ratio of resistors R_1 plus R_2 to the total of R_1 plus R_2 plus R_3. Similarly, when the selector switch is moved to position 3, the voltage across R_1 will be all that causes the meter deflection. Proper choice of resistance permits any desired range extension.

This circuit has the advantage of presenting a constant d.c. impedance to the supply source regardless of the range chosen (provided there is no excessive leakage in the grid circuit of the vacuum tube).

Except for improved sensitivity, which we will discuss in a moment, the v.t.v.m. shown in Fig. 4 contains all the features that we said earlier would be desirable for the simpler circuit

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in Fig. 2. As it stands, it is a sensitive and reliable voltmeter. It can also be used to measure current merely by inserting a small known resistor in series with the circuit carrying the current and measuring the voltage across the resistor with the v.t.v.m. Ohm's Law ($I = E \div R$) does the rest.

Finally, this v.t.v.m. can also be used to measure resistance, as shown

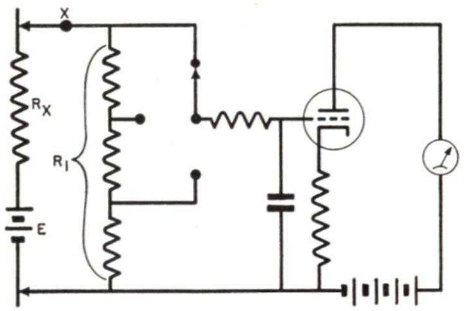

FIG. 5. Using the v.t.v.m. to measure resistance.

in Fig. 5. Here, the battery E is a known voltage source, R_1 is the lumped input resistance of our v.t.v.m., and R_x is the resistance we want to measure. Here's how we do it.

First, the battery is connected between the terminals of the v.t.v.m. This puts the battery right across resistor R_1, and we get a deflection of our v.t.v.m. corresponding to the battery voltage. Usually the voltage is adjusted to give a full-scale meter deflection.

When the unknown resistance R_x is inserted in the circuit, the battery current flows through both R_x and resistor R_1. This divides the voltage so the voltage drop across resistor R_1 is less than the total battery voltage. If resistor R_x exactly equals resistor R_1, the voltage divides in half and we get a half-scale meter deflection. You remember that this is just how a regular ohmmeter works. Therefore, we can calibrate the v.t.v.m. scale in ohms as we do with any other ohmmeter.

The arrangement in Fig. 5 is much better than an ordinary ohmmeter for measuring high resistances. Resistor R_1 may be 10 megohms, which would give us a 10-megohm center-scale reading on our meter. Since we can read 100 times the center-scale value on an ohmmeter, this means we can readily measure unknown resistors as high as 1000 megohms, using only 3 volts or so as E. If we increase E to, say, 300 volts, and insert at X a 990-megohm resistor, we can increase the range to 100,000 megohms. Compare this sensitivity with that of an ordinary ohmmeter, where 300 volts may give a range of only 10 or 15 megohms!

Low resistances can also be measured by shunting R_1 with a small resistor or replacing it with a low ohmic value to lower the center-scale value. If we make R_1 100 ohms, the mid-scale ohmmeter reading will be 100 ohms, and we can calibrate our meter accordingly.

Since a v.t.v.m. can measure voltage, current, and resistance, it can be made into a multimeter. The proper ranges and functions can be obtained by using switches; proper calibration will permit direct scale readings.

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Improved D.C. Vacuum Tube Voltmeters

The circuits so far covered have been simple. They will work satisfactorily in measuring fairly high voltages. Now let's see how better d.c. vacuum tube voltmeters can be made.

Meter Sensitivity. So far, we've been letting the normal plate current of the tube give our meter a mid-scale deflection. This has meant that we've had to use a fairly insensitive meter.

For example, if the normal plate current is 10 ma., we must use a 20-ma. meter to have this current cause a mid-scale deflection. Then, the applied voltage must cause a 10-ma. plate current change to give us a full-scale deflection. Even if the tube has a high mutual conductance, a 10-ma. plate current change requires a fairly high grid voltage, so the basic range of our v.t.v.m. is high. This means low voltages produce only small changes in plate current and are not easily read.

But if our meter reads zero when no voltage is measured, we can use a much more sensitive meter—1 ma., for example. To do so, we must find some means of having zero plate current when there is zero grid input.

Several kinds of circuits have been developed for producing this effect, including some in which the normal plate current is bucked out by an equal and opposite current from a separate battery, and others in which a high bias is applied and the tube is worked at or near the plate current cut-off point. The most generally satisfactory circuits, however, use the bridge principle. Let's see how they work.

D.C. BRIDGE V.T.V.M.

You will study the bridge circuit in more detail later, so here we'll just go into the basic principles briefly. A typical bridge is shown in Fig. 6.

When a voltage is applied across terminals A and B, current flows through R_1 and R_3, as well as through R_2 and R_4. If we make R_1 equal R_2 and R_3 equal R_4, the resistance of R_1 plus R_3 equals R_2 plus R_4, so the current through path A-C-B equals that through path A-D-B. This makes the voltage drops across R_1 and R_2 equal, so the potential of point C with respect to A is the same as that of D with respect to A. Hence, points C and D are at the *same potential* (no voltage difference between them)—and *no current* flows through the meter. The bridge is said to be "balanced" when the meter reads zero.

When either pair of resistors is made unequal (R_1 not equal to R_2, or R_3 not equal to R_4) there will be a voltage difference between C and D, so current will flow through the meter. The bridge is now unbalanced.

To use this bridge principle in our v.t.v.m., we set up the circuit shown

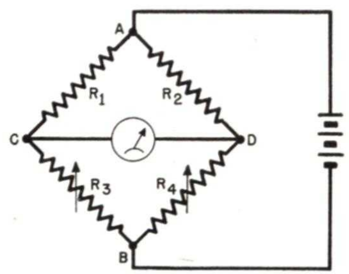

FIG. 6. A resistance bridge.

in Fig. 7. This is much the same as the circuit in Fig. 6, except that we've replaced variable resistor R_3 with a tube and bias resistor R_6. Resistors R_1 and R_2 are equal in value.

With no input on the grid, we balance this circuit by adjusting R_4 until no current flows in the meter. As you just learned, this means that R_4 equals the plate-cathode resistance of the tube plus the resistance of R_6.

Now if we apply an input to the grid through terminals X and Y, the grid voltage changes the plate current.

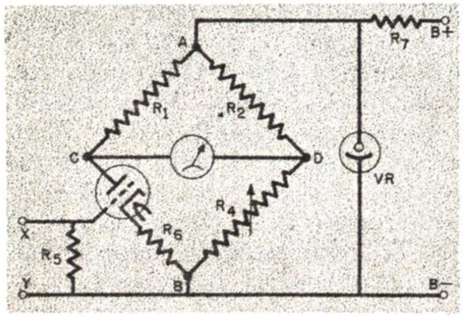

FIG. 7. Using a tube in a bridge in place of a resistance leg.

This current change means the plate-cathode resistance has changed—so the bridge is unbalanced and current flows through the meter. Calibrating the meter in terms of voltage input to the grid gives us our v.t.v.m.

Regulating the Power Supply. It is usually preferable to use a power pack for our bridge type v.t.v.m. instead of a battery. But such a power supply must be very well regulated. Changes in the supply voltage will shift operation of the tube to a different part of its characteristic, and, as you know, this destroys the calibration of the v.t.v.m.

One common method of regulation, using a voltage regulator tube VR and a series resistor R_7, is shown in Fig. 7. This tube has the property of passing a much higher current when the voltage across it increases slightly. The voltage drop this current causes in resistor R_7 then drops the voltage across VR. The net effect is to keep the voltage across VR, which is the voltage supplied to the v.t.v.m., very nearly constant. Under normal conditions, a modern regulator tube can maintain the voltage across its terminals within 2 or 3 volts of its rated value.

An Improved Circuit. An even better bridge type v.t.v.m. circuit is shown in Fig. 8. Here a tube exactly like the first one is used in place of resistor R_4 of our original circuit.

The use of two tubes tends to cancel the effects of any change in supply voltage. If the supply voltage increases, the plate current to both tubes increases correspondingly and the bridge remains in balance; a regulator tube is thus unnecessary.

Resistors R_6 and R_8 are used to make the tubes bias themselves. This also helps keep the circuit in balance.

An unusual feature of the circuit in Fig. 8 is the use of R_7 to get greater stability and higher sensitivity. Both plate currents flow through this resistor, producing a voltage having the polarity indicated, so more self-biasing is produced. However, this bias voltage is high enough to cut the tube currents off except for the fact that it is bucked out by a positive voltage from R_{10}. (Trace the grid circuits to ground,

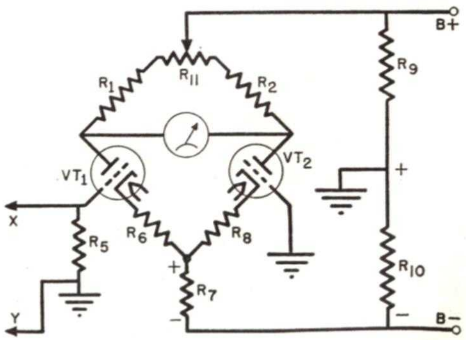

FIG. 8. A balanced tube bridge.

to the junction of R_9 and R_{10}, then through R_7 to each cathode to see this.) Now the resulting net bias is about that of each cathode resistor.

When a voltage is applied to the input of VT_1, making terminal X positive with respect to Y, the plate current of VT_1 increases. This causes an increased flow of current through R_7, thus biasing the grid of VT_2 more negatively. (The positive R_{10} drop remains fixed, but the negative R_7 drop increases, so the net effect is more negative bias on VT_2.) Therefore, the plate current of VT_2 goes down.

Courtesy RCA

FIG. 9. The RCA-Rider Volt-Ohmyst Jr. is a typical d.c. type v.t.v.m. using the balanced bridge circuit.

Since the plate resistance of VT_1 goes down at the same time the plate resistance of VT_2 goes up, this bridge becomes much more unbalanced for a given input than does the circuit in Fig. 7, and so is more sensitive. Also, the v.t.v.m. in Fig. 8 can be made more linear-reading than the Fig. 7 v.t.v.m. by choosing tubes whose characteristics balance each other.

An exact balance of the bridge (zero meter adjustment) is obtained by adjusting R_{11}. Varying this resistor varies R_1 and R_2, adding to one and subtracting from the other. This varies the tube plate voltages, so the tube resistances change also. If the ratio of R_1 to R_2 is made the same as the ratio of the tube plate resistances, the two paths will adjust themselves so that the same voltage drops occur, even though the currents are unequal. This ratio is usually given as $\frac{R_1}{R_2}=\frac{R_{VT1}}{R_{VT2}}$. Notice that it is not necessary that $R_1 = R_2$ or $R_{VT1} = R_{VT2}$, just so the ratio of values is properly chosen.

A typical commercial bridge instrument is the RCA Junior Volt-Ohmyst shown in Fig. 9. Its circuit is basically that of Fig. 8, with provisions to extend ranges and measure resistance.

A.C. Vacuum Tube Voltmeters

You recall that most standard a.c. voltmeters have distributed inductance and capacity that ruin calibration when you try to use them on high-frequency a.c. Highly sensitive a.c. vacuum tube voltmeters have been developed that are relatively free from frequency errors and limitations, even at r.f. Let's see how they work.

A TRIODE A.C. TYPE V.T.V.M.

You learned that the v.t.v.m. shown in Fig. 2A won't indicate on a.c. because the tube is worked on a straight part of its characteristic. Thus, an a.c. grid input produces an a.c. plate current varying around the normal plate current—and the *average* of this a.c. plate current (which is all the meter can read) is just the same as the normal plate current. (See Fig. 10.)

But by changing the bias so as to move the operation to the curved part of the characteristic, we get the de-

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tector action shown in Fig. 11. Now there is little or no plate current when no signal is applied to the grid. When an a.c. voltage is applied, rectified pulses are produced that have an average different from the no-signal plate

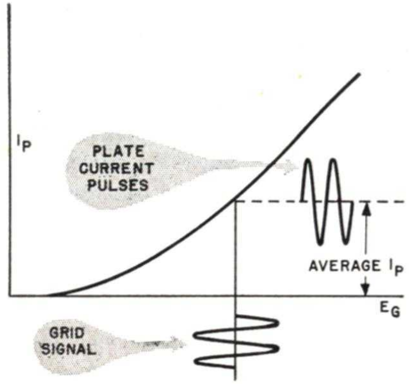

FIG. 10. The d.c. average of the plate current does not change when an a.c. voltage is applied to a class A amplifier.

current. This difference in average plate current can be read on a meter.

Sensitivity. With this change in operating point, the circuit in Fig. 2A will read both d.c. and a.c. voltages, provided the d.c. voltage has a polarity that makes the grid positive. However, because of the curve of the tube characteristic near plate current cut-off, very little meter deflection is obtained for small voltages, so the scale is hard to read at the low end.

As the applied voltage is increased, the meter deflection becomes more nearly linear, so this circuit is satisfactory for fairly large voltages. Further on in this Lesson we'll take up circuits for measuring low voltages.

Frequency Range. We can measure high-frequency voltages on our a.c. vacuum tube voltmeter. The limit to which we can go before the scale calibration becomes inaccurate is determined primarily by the input circuit of the v.t.v.m. and the circuit where measurements are being made. The input capacity of the tube is in parallel with the grid resistance. As frequency goes up, the reactance of this input capacity goes down. This reduces the impedance between the input terminals, so our v.t.v.m. will eventually start loading the circuit across which it is connected.

This loading is not so serious when the v.t.v.m. is connected across a tuned circuit. Since the v.t.v.m. is primarily a capacitive load, it will detune the resonant circuit. If we retune the circuit with the v.t.v.m. in place, we can automatically cancel this effect and make our measurements.

Test Lead Effects. In measuring r.f. voltages, it is desirable to use a shielded test lead for our v.t.v.m. Shielding prevents the lead from picking up hum or other stray voltages that would produce false readings. However, the capacity between the shielded lead and the shield is in parallel with the tube input capacity. This further loads the measured circuit, so a

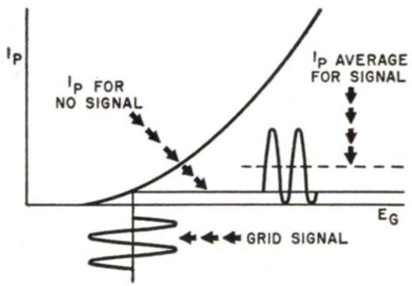

FIG. 11. By moving to the curved portion of the characteristic, there will be a d.c. average change from the no-signal value, when an a.c. voltage is applied.

shielded lead limits the frequency range.

Test Lead Resonance. Test leads become resonant whenever their length equals a quarter wavelength at the frequency where measurements are made. At a frequency of 75 megacycles (4 meters), leads about 3 feet long would be a ¼ wavelength line.

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As you know, a quarter-wave line has an unusual voltage distribution. If we apply a high voltage to one end, we get very little or no voltage at the other end. Obviously, this would make our reading highly inaccurate.

Although this quarter-wave effect occurs only at resonance, the test leads begin to affect the voltage at frequencies considerably lower. In general, a v.t.v.m. using test leads cannot be used for voltages with frequencies greater than one or two megacycles, unless special calibration charts are provided. This is still quite an improvement over the standard a.c. voltmeter. Later on,

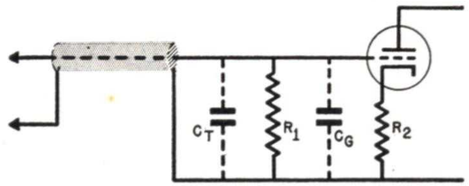

FIG. 12. The input circuit of an a.c. type v.t.v.m.

we will see how voltages can be measured at higher frequencies.

Extending A.C. Ranges. The input circuit for the basic range of our v.t.v.m. is similar to the circuit shown in Fig. 12 where we have input resistance R_1 shunted by C_T and C_G, the test lead capacity and the tube input capacity respectively.

If we try to use the voltage-dividing circuit shown in Fig. 13 that worked so well for d.c., we find that C_G causes trouble. Moving the selector switch to position 2 shunts C_G across resistors R_2 and R_3. Since the reactance of C_G varies with frequency, the impedance of C_G in parallel with R_2 and R_3 will vary with frequency, whereas the resistance of R_1 will remain constant. Then the voltage division across the divider will also vary with frequency—so the range we get at position 2 (or 3) will depend on the frequency of the input voltage.

We can clear up this difficulty by using a capacitive voltage divider like that shown in Fig. 14. When the v.t.v.m. is used to measure a.c. voltages, the division of voltages across this divider is determined by the re-

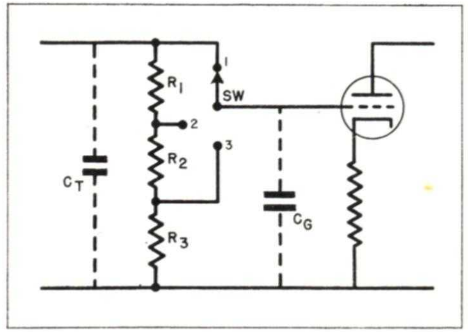

FIG. 13 The tube capacity upsets the voltage division as the switch is rotated.

actances of the condensers. In position 2, the a.c. voltage division is determined by the reactances of C_1 and C_G. In position 3, C_2 is added to C_1, so the combined reactance to that of C_G is the divider. Since these react-

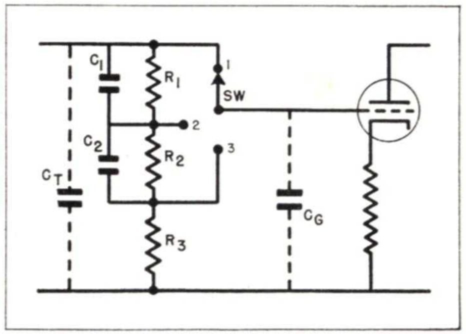

FIG. 14. This capacity voltage divider gives uniform a.c. voltage division.

ances all vary in the same manner when the input frequency varies, the division of voltages remains the same, and the various ranges of our v.t.v.m. are therefore very nearly independent of frequency.

This v.t.v.m. circuit may also be

used to measure d.c. voltages. In this use, the condensers have no effect and the resistors determine the voltage division for the ranges, just as they did in the circuit shown in Fig. 4.

A.C. WAVE SHAPES

You recall that an a.c. cycle has a peak value, an average value, and an effective value. Because we are usually most interested in the r.m.s. value of a sine wave, we calibrate an a.c. type of v.t.v.m. to indicate r.m.s. values.

But the meter of an a.c. type v.t.v.m. actually operates from the *average* of the plate current. Now the average plate current is not the same as the effective or r.m.s. value—so we have a meter that really operates on one value of an a.c. wave but is calibrated to indicate another.

This is perfectly all right as long as the ratio of the r.m.s. value to the average value is constant—as it is for any regular wave shape. If you want to determine the average value of the a.c., all you have to do is multiply the meter scale reading by the proper multiplying factor. The peak value can also be determined in the same way (using a different factor, of course).

But you must remember that the exact ratios between the r.m.s., average, and peak values of a wave depend on the wave shape. Fig. 15 shows the relationships existing in various kinds of waves. Notice that all these waves have a *different* peak-to-average-to-r.m.s. relationship. (The special wave of Fig. 15E is similar to television control pulses and has widely different r.m.s. and average values, depending on the height and width of the pulses as well as their spacing.)

Distorted Waves. The meter of the usual v.t.v.m. is calibrated to read r.m.s. values when the instrument is measuring a pure sine wave. The readings may be in error if such a v.t.v.m. is used to measure a distorted wave, because the distorted wave will probably not have the same average-to-r.m.s. relationship as a sine wave.

Suppose we start with a sine wave, but one stage distorts the wave as shown in Fig. 16. One-half the wave is practically square, whereas the other half remains a sine wave. This is commonly the result of operating an amplifying tube too near cut-off.

If we apply our test leads in such a manner that the sine portion of this wave makes the grid of the v.t.v.m. more positive, we'll get an indication

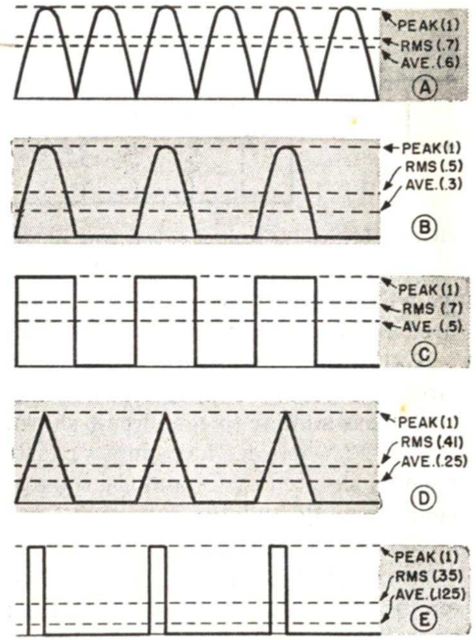

FIG. 15. The shape and size of the wave pulse determines the relationship between the peak, average and r.m.s. values.

that corresponds to the effective value of the sine wave.

On the other hand, if we reverse the test leads, the rectifying action of the v.t.v.m. will cut off the sine wave portion and we will get an indication corresponding to the distorted half of the cycle. This will give us an entirely different reading from the first one, because the relationship between the peak, average, and effective values will be different. Distorted waves of this

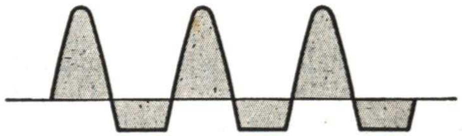

FIG. 16. A distorted wave, such as might be produced by operating a tube at the wrong point on the characteristic.

kind cause more error with a *peak* v.t.v.m. (to be studied later) than with the *average* types already discussed, because the peak is always very different from the r.m.s. value whereas the average and r.m.s. values are usually fairly close to each other.

Reversing the v.t.v.m. leads may produce different readings even on an undistorted wave, because of the difference in capacity to ground between leads or parts in the v.t.v.m. The different readings caused by reversing leads is an effect known as "turnover."

Usually a shielded cable is provided to connect the v.t.v.m. to the circuit being tested, with the shield used as one of the probes. Since the shield is always connected to an r.f. grounded point in the circuit, the hot probe will always be the probe for measuring voltage, and it will not be possible to reverse the probes. Remember, however, that each amplifying stage reverses the phase of a signal 180°—which produces exactly the same effect as reversing the leads—so it is still possible for distortion to produce an error in the reading as we go from stage to stage.

Peak Vacuum Tube Voltmeters

Several types of a.c. vacuum tube voltmeters have been designed that measure the peak value. One of the simplest is shown in Fig. 17. Here's how it works.

When the plate of diode VT is made positive by the voltage source, condenser C_1 is charged. When the cycle reverses, the tube stops conducting and C_1 starts to discharge through R_1. However, R_1 is so large that condenser C_1 does not have time to discharge much before the cycle reverses and charges it up again. Fully charged, C_1 has a voltage equal to the source voltage peak. After some charge has leaked off during the half cycle the tube does not conduct, the voltage drops somewhat. When the cycle reverses again, the tube can't conduct until the source voltage becomes higher than the reduced condenser voltage. When the tube does conduct, the condenser is charged to full source voltage almost at once.

The net result of this circuit action is that C_1 always has a voltage very

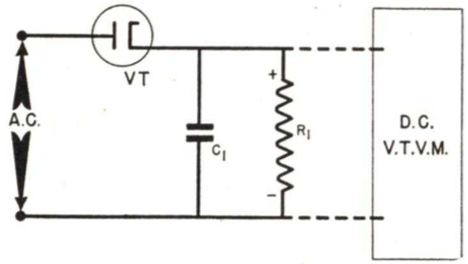

FIG. 17. A simple diode peak-indicating a.c. type v.t.v.m.

near the peak voltage of the source. This voltage is d.c.—so we measure it with a d.c. type v.t.v.m. This gives us a sensitive way of measuring the peak voltage of the a.c. source.

Since it draws current from the source only at the peaks of the applied

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voltage, this v.t.v.m. acts as if it had a very high resistance. When used to measure r.f. voltages, the amount it loads the source depends mostly on the capacity between the input terminals. The plate-cathode capacity of the tube is in series with condenser C_1 across the terminals, but condenser C_1 offers low reactance to r.f., so the loading depends mostly upon the internal tube capacity.

An Improved Circuit. An even better circuit is shown in Fig. 18. Here's how it works.

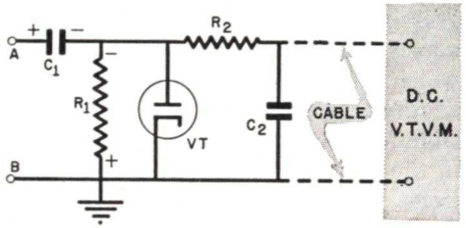

FIG. 18. An improved peak v.t.v.m.

During the half of an input a.c. cycle that makes terminal A positive with respect to terminal B, the diode conducts. Electrons flowing through the tube charge C_1 to the peak source voltage, with the polarity shown.

When the cycle reverses and the tube ceases to conduct, the voltage on the condenser and the input voltage combine to cause an electron flow through R_1. However, the time constant of C_1 and R_1 in series is so high that C_1 discharges only a little during this time. C_1 is thus only a little below the source voltage when the cycle reverses again. As soon as the source voltage rises above the voltage on C_1, the tube conducts, and C_1 is rapidly charged to full peak voltage.

Thus this circuit acts in much the same way as the previous one—almost the full peak voltage remains on C_1 all the time, and the circuit draws current from the source only when the peak value exceeds the C_1 voltage.

The voltage indications are obtained from the d.c. type v.t.v.m., which is connected through filter R_2-C_2 so that it measures the voltage across R_1. Any r.f. across R_1 is prevented from getting to the v.t.v.m. by this filter.

On the half cycle when terminal B is positive, the voltage across C_1 and the source voltage combine to force a small current through the high resistance, R_1. The resulting voltage drop across R_1 has a d.c. average that operates the v.t.v.m. On the other half cycle, the source voltage and that across C_1 buck or oppose each other. Hence, there is practically no current through R_1 on this half cycle.

At low frequencies, the time between reversals of the input voltage may become so great that nearly all the charge leaks off C_1. The circuit then ceases to be a peak-indicating device. However, it is easy to give C_1 and R_1 such a high time constant that the frequency at which this effect occurs is quite low.

The amount this circuit loads the measured circuit depends on the plate-cathode capacity of the tube and on stray capacity between the terminals and between C_1 and ground. By using a tube with extremely low capacity, such as one of the modern acorn-type tubes, we can reduce this capacity so that very high frequencies can be measured. In fact, we can mount the tube right in the test probe, and so eliminate most of the difficulties with test leads that you learned about earlier in this Lesson. Fig. 19 shows an instrument equipped with such a probe that can be used to measure voltages at several hundred megacycles.

There are three important things to remember about this type of v.t.v.m.:

1. It can be made fairly sensitive.
2. It can be used at extremely high frequencies.
3. It will not load the measured circuit much.

It is possible to change the range of a v.t.v.m. of this type by using a multi-range d.c. vacuum tube voltmeter.

The peak v.t.v.m. is more sensitive than average-indicating types, because the peak value of a wave is almost always reasonably high—whereas the average voltage may be quite low. However, since a peak v.t.v.m. is usually equipped with a meter calibrated to indicate r.m.s. values, it may give incorrect readings on distorted waves.

Courtesy General Radio Co.

FIG. 19. A v.t.v.m. capable of measuring r.f. voltages up to several hundred megacycles. An acorn-type tube is mounted right in the probe unit to reduce input capacity and make such high-frequency voltage measurements possible.

SLIDE-BACK V.T.V.M. CIRCUITS

There is another kind of v.t.v.m. used to measure peak values. It is known as the "slide-back" type.

A typical circuit is shown in Fig. 20. In using it, the slider of potentiometer P is first moved to point 1. The voltmeter V_M then reads zero. Next, with no signal applied (terminals A and B shorted together), the small tube current is read on meter I_M. This is not quite zero, because contact potential within the tube causes a small amount of current flow. The exact *amount* of current does not matter, just so we remember it.

Then the voltage to be measured is applied between terminals A and B. This causes a current flow through the meter I_M and through resistor R_1. Resistor R_1 and condenser C_1 can be so chosen that this current will cause a meter deflection proportional to the peak value of the applied voltage.

Now, with the signal still applied, potentiometer P is adjusted to bring the pointer of current meter I_M back to its initial position. In other words, P is used to introduce a bucking voltage from the battery into the circuit. When this bucking voltage just brings I_M back to its initial reading, it is equal to the peak signal voltage. Then all we have to do is read the bucking voltage on meter V_M, and we know what the peak voltage is.

This circuit has several advantages. We don't have to calibrate meter I_M, because we use only its initial pointer position. Also, the characteristics of the tube and other parts aren't very important. In fact, the accuracy of the measurement in a properly adjusted circuit depends only on the accuracy of the d.c. meter V_M. However, you must be sure to adjust the potentiometer just enough to bring I_M back

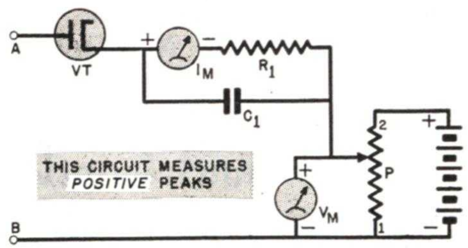

FIG. 20. A positive-peak slide-back v.t.v.m.

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to its initial reading and no farther, to prevent errors in the reading.

Negative Peak Indicator. The circuit in Fig. 20 works whenever terminal A is made positive with respect to terminal B. Therefore, this device indicates on d.c. as well as a.c.

Should the polarity be reversed or

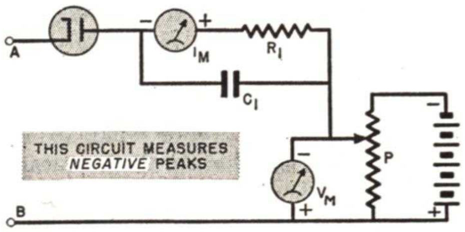

FIG. 21. A negative-peak slide-back v.t.v.m.

should we want to measure the other half of the a.c. cycle, we can reverse the terminals A and B. Sometimes it is not wise to do this, for there may be capacity effects that would affect the readings. Also, it may be desirable to ground terminal B.

These possible difficulties make it better to leave terminals A and B connected as before, and change the circuit as shown in Fig. 21. Here the diode, the meter I_M and the slide-back battery have been reversed. Now, when terminal A is negative (B is positive), the diode passes current and the instrument works as before—except that it measures the negative peaks.

Triode Slide-Back V.T.V.M. You can use a triode tube as a slide-back v.t.v.m., as shown in Fig. 22. With terminals A and B shorted, the C bias is adjusted to give some particular plate current I_M. Then the maximum slide-back voltage is introduced by potentiometer P. With the unknown voltage now applied to terminals A and B, the potentiometer setting is reduced until the meter I_M returns to

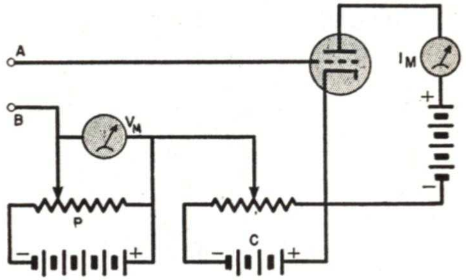

FIG. 22. A triode slide-back v.t.v.m.

its original reading. The V_M reading is then equal to the peak voltage applied.

This circuit can only be used to measure positive peaks. However, it causes less loading of the source of voltage, because the grid circuit draws no current from the source.

Coil and Condenser Measurements

In past Lessons you have studied inductance, capacity, impedance, reactance, power factor, and the Q factor possessed by coils and condensers at audio and radio frequencies. Now we are going to learn how to measure these properties.

Such measurements are made by using a circuit that allows the part in question to be compared directly or indirectly with a standard part. Usually some ratio circuit is used in making comparisons, so that fewer standard parts—which are very expensive—are needed. If the ratio test circuit is put together on the workbench, some simple calculation is required, using either Ohm's Law, or simple multiplication or division. However, factory-made, precalibrated capacity bridges, Q factor meters, inductance bridges, and other measuring apparatus are available with direct-reading dials that can be read directly.

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The method used to make the measurements depends on the accuracy desired and on the apparatus available. If coils had only inductance, condensers only capacity, and resistors only resistance, measurement would be vastly simplified. Instead, coils have distributed capacities and both a.c. and d.c. resistances; condensers have resistances and inductances; and resistors may have inductances that, though small, are quite effective at higher frequencies. Measurements must either take all these factors into account or be somewhat in error.

It is entirely possible that you, as a communications man, will seldom or never have to make accurate measurements of the properties of a coil, a condenser, or a resistor. However, it is important for you to know how such measurements are made, both because you may have to make them occasionally (particularly if you build any equipment) and because a good communications man always knows more about his field than he has to know to do his particular job. That, in fact, is the way men advance in any profession.

We are going to show you a number of methods of making measurements. Some use formulas, and in some cases we show how the formulas are obtained. We do not intend that you try to memorize the methods, the formulas, or the process of getting the formulas —they are presented here for your future reference, and you can come back to this Lesson should you need information. We cover the field here, so you will have some idea of the measurements required in all branches of radio and will not have to start in absolutely green should you go into any field of radio requiring this information. You will probably never use all the methods described, no matter where you go, so just learn the basic principles of the methods and answer the Lesson questions.

Let us now see how measurements are made. We'll start with air-core inductances, then take up iron-core coils, condensers, resonance methods, and bridge methods.

Inductance of Air-Core Coils

The inductance of an air-core coil can be found from its physical dimensions—such as length and diameter of the coil, the number of turns, and size of wire. You can then use these values with an inductance design chart or formula to determine the inductance within a few per cent. These charts or formulas are found in engineering handbooks and radio publications.

However, at the time you need them, charts are not always available; they cannot be used when tolerance limits are being determined, nor do they give the Q factor. So now let us study actual inductance measurements.

We can find the inductance of an air-core coil by determining the coil reactance and calculating the inductance, by direct comparison methods, or by using bridge or resonant circuit methods. Since the last two can also be used to measure capacity and resistance, they will be covered in another section of this Lesson. Let us now take up the reactance and direct comparison methods.

REACTANCE METHOD

A very simple method that can be used on air-core coils is to apply a known a.c. voltage to the coil and measure the current flow. From Ohm's

Law for a.c. circuits, you know that the impedance of the circuit equals the voltage divided by the current flow ($Z = E \div I$). Also, you know that the impedance Z is a combination of the a.c. resistance and the reactance of the coil. ($Z = \sqrt{R^2 + X_L^2}$). If you neglect the a.c. resistance, the impedance is the same as the reactance of the coil. Once you find the inductive reactance, you can find the inductance from the formula $X_L = 2\pi fL$, which is easier to use if arranged in the form $L = X_L \div 2\pi f$.*

Unfortunately, this method is rather inaccurate. For one thing, the a.c. resistance, which you must neglect, may be considerable. Further, the measurement must be made at radio frequencies, because the coil reactance is usually negligible at lower frequencies. Usually a signal generator is the only convenient source of r.f. voltage for the

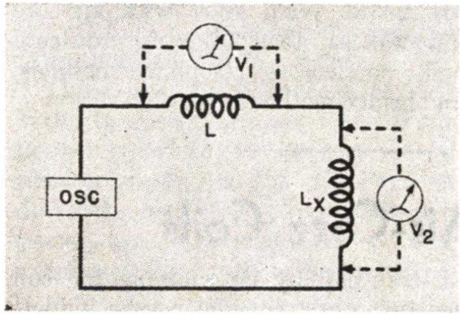

FIG. 23. The comparison method used for an air-core coil.

measurement, and such instruments are seldom extremely accurate in their calibration; of course, any error in your determination of the frequency will cause a similar error in the result. Finally, both voltage and current must be measured; these measurements are difficult to make accurately at radio

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*L = inductance in henrys
X_L = inductive reactance in ohms
f = frequency in cycles
2π = 6.28, a constant

frequencies, and, here again, any measurement error will affect the result. For these reasons, this method is usable only if errors of 10% to 20% are permissible.

COMPARISON METHODS

If a known inductance is available, you can place the unknown inductance in series with the calibrated one, apply an r.f. voltage to the combination (as shown in Fig. 23), and get the voltage readings. The voltage drops are proportional to the impedances. If we ignore the coil a.c. resistance, then the voltages are proportional to the reactances, which in turn are proportional to the inductances, so we can say that $\frac{V_1}{V_2} = \frac{L}{L_x}$ or $L_x = \frac{V_2 L}{V_1}$. Thus, to find the inductance of L_x, multiply the inductance of L by the voltage V_2 and divide by the voltage V_1. For best results, the standard should be near the value of the unknown, so the voltmeter readings will be similar.

If a variable standard inductance is available, use it as L, then adjust the variable standard inductance until the voltage drops across the two coils are equal. Then the impedances of the two coils are equal and, neglecting resistance again, you can read the unknown inductance directly from the calibrated scale on the variable standard inductance. This method has many advantages over the reactance method. For example, you do not have to know the frequency of the source—and if identical voltmeters are used across each coil or the same one is moved from coil to coil, even the accuracy of the voltmeter does not matter. However, some error may be caused by neglecting the resistance of the two coils, which may differ.

Three-Voltage Method. A simple and accurate measuring circuit is

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shown in Fig. 24A. The resistance of R must be known (or measured) accurately. Preferably, R should have a resistance such that E_R is somewhere near the value of the voltage E_Z, but this is not necessary.

After making the three voltage measurements shown in Fig. 24A, you must draw a graph. To do this, first mark a horizontal line on a sheet of paper, such as the line O-A in Fig. 24B. Along this line, measure off a distance proportional to the voltage found across resistor R. Any satisfactory scale can be used, such as 10 volts to the inch. After you have measured the proper length along this line from point O with a ruler, mark point B. The distance O-B is then proportional to the voltage E_R.

Now, take a compass (a drawing instrument similar to a pair of dividers, with a pencil attachment) and adjust the compass so that the distance between its point and its pencil is proportional to the voltage E_S, using the same scale of volts-per-inch used for laying out the line O-B. With the compass point set at point O, draw an arc or semicircle with the compass.

Next, adjust the compass so that the distance between its point and pencil is proportional to voltage E_Z, using the same volts-per-inch scale as before.

With the compass point now set at point B, draw an arc with the compass that crosses the arc you made from point O. The point where they cross is point C in Fig. 24B. Now, draw lines from C to B and from C to O. The line O-C is then proportional to the voltage E_S, and the line B-C is proportional to the voltage E_Z.

Next, drop a vertical line (line C-D) from point C at right angles to line O-A. You can use the right (90°) angle of a triangle to do this.

You have now formed a triangle having as its sides the lines B-C, B-D and C-D. Since line B-C represents the voltage across the coil *impedance*, line C-D is proportional to the voltage drop across the inductive reactance alone, and line B-D is proportional to the voltage drop across the coil a.c. resistance. The combination of these two

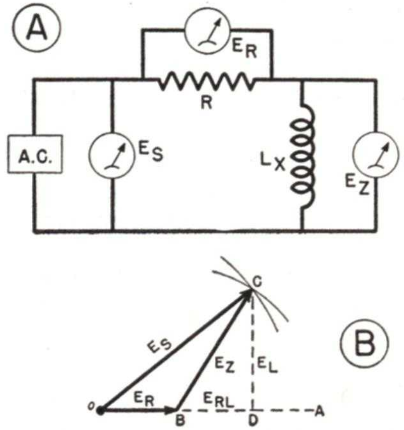

FIG. 24. The three-voltage method. Not only is this method more accurate, but it can also be used when only a voltmeter is available.

voltages makes up the total voltage drop across the coil, which you have found to be E_Z.

Now since the voltage E_L is caused by the reactance alone, dividing this voltage by the current will give you the true coil reactance. The voltage E_L can be determined by measuring the line C-D with a ruler, then converting the number of inches into volts, using the volts-per-inch scale you used to draw the other lines.

The current is, of course, equal to the resistor voltage E_R divided by R. Compute this current, divide E_L by it, and you have the coil reactance. You can now find the true inductance from the formula $L = X_L \div 6.28f$.

This method eliminates one error by taking the coil a.c. resistance into account. Using identical voltmeters (or the same one), your accuracy depends only on the accuracy with which the resistance is found, the accuracy with which the frequency is known, and the care used in drawing the graph. Make the graph as large as possible (fewer volts-per-inch scale) for greatest accuracy.

The three-voltage method also lets you determine the Q factor of the coil at the frequency of measurement. You know the Q factor is equal to the reactance of a coil divided by its a.c. resistance ($Q = X_L \div R$). Since the coil resistance and coil reactance are effectively in series, with the same current through each, the reactance and resistance are proportional to their voltage drops. Therefore, you can find the Q factor directly by dividing voltage E_L by voltage E_{RL}.

Other Methods. You can also measure inductance by using various bridge circuits and resonant circuits. Since these methods can also be used to measure capacity, they will be discussed later in this Lesson.

Inductance of Iron-Core Coils

You cannot determine the inductance of an iron-core coil except by electrical measurements, because its physical size does not indicate its inductance. The methods of measuring the inductance of an iron-core device are somewhat similar to those already discussed for air-core coils. However, you must measure the inductance under the operating conditions that will exist in the apparatus, because the inductance depends on the core flux density. If the coil is used in a circuit where d.c. flows through it, you must approximate the same d.c. flow during tests. You must also have about the same a.c. flow as in normal operation, and the frequency used for measurement must be within the normal range of the device.

If the iron-core coil is used in a circuit where no d.c. normally flows, its inductance can be measured by the methods used for an air-core coil as long as a normal a.c. voltage and frequency are employed. With a transformer, you must remember that you are determining the inductance of only the one coil which is connected in the measuring circuit. The inductance of the other windings must be determined separately. Also, to find the actual operating inductance of any winding, you must connect the normal loads to all the windings of the transformer—even to those not being measured.

POLARIZING CURRENT

Usually an iron-core coil will have both d.c. and a.c. flowing through it. As you know, you must send normal amounts of both a.c. and d.c. through such a coil to measure its inductance under working conditions. A circuit for doing so is shown in Fig. 25.

In this circuit, coil L_x is the inductance under test. The battery B causes d.c. to flow through the coil; this current is read on I_{DC} and adjusted to the required value by resistor R.

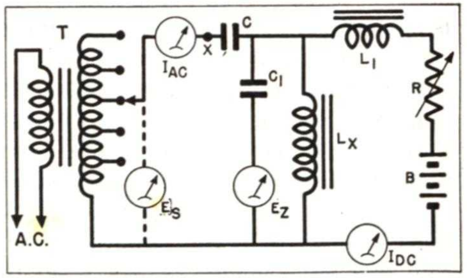

FIG. 25. Iron-core coils require a polarizing current, so this circuit is used.

A.C. is applied through transformer T and condenser C. Condenser C prevents d.c. from flowing through the secondary of transformer T, and choke coil L_1 prevents a.c. flow through the battery and R. Thus, d.c. flows only from battery B through R, L_1 and L_x, and a.c. flows only from the transformer through C and L_x.

Condenser C should have a large capacity, so its reactance will be negligible. Also, L_1 must be a high-inductance coil, so the a.c. flow through L_1-R-B (in parallel with L_x) will be negligible.

After the d.c. has been adjusted to approximate the amount that normally flows through the coil, a tap on the secondary of transformer T is chosen that produces about the normal a.c. voltage drop across coil L_x, as indicated by E_Z. (This meter must measure a.c. only, so blocking condenser C_1 is placed in series with it.) Then the current meter I_{AC} is read. Dividing the voltage E_Z by the alternating current gives the impedance of the coil L_x. If the a.c. resistance of the coil is assumed negligible, the impedance is approximately the same as the reactance of the coil, and the inductance can be found from the formula $L = X_L \div 6.28f$.

However, most iron-core coils are low-Q devices, having large windings with appreciable a.c. resistance that cannot be ignored. To eliminate the large error introduced by assuming the impedance equals the resistance, measure the inductance of such coils by the three-voltage method already described. To do so, first insert a known resistance at point X, then adjust the d.c. to the proper value and measure: 1, the voltage E_S; 2, the voltage across the resistor at X; and 3, the voltage E_Z. Then use the same procedure followed for Fig. 24B.

Condenser Capacity

We normally deal with three kinds of radio condensers; air-dielectric (usually variable), solid-dielectric, and electrolytic. Next to tubes, solid-dielectric and electrolytic condensers cause more troubles than any other parts. Although ohmmeter measurements or part substitution will show up most of these defects, condenser measurements are required frequently enough so that test equipment manufacturers have brought out capacity testers. These will be described shortly, when we take up bridge circuits.

SOLID-DIELECTRIC CONDENSERS

Let us first see how to measure capacities of ordinary solid-dielectric by-pass condensers — paper, mica, ceramic, and similar types. The methods we will now discuss are satisfactory for capacities above .01 mfd.

Reactance Methods. Condenser capacity can be measured in almost exactly the same manner as coil inductance, by measuring the applied a.c. voltage and the current flow. It's wise to determine first whether the condenser is short-circuited, since the alternating current meter can be damaged by excess current. Also, be sure the applied a.c. voltage peak is well below the peak voltage rating of the condenser.

After measuring the a.c. voltage and current, you can find the impedance by dividing the voltage by the current. Since the a.c. resistance of the normal solid-dielectric condenser is negligible at low frequencies, you can say that the reactance equals the impedance and then use the formula for capacitive reactance, $X_C = \frac{159{,}000}{fC}$ (where

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f is in cycles per second and C is in microfarads), to find the capacity. This is usually converted to the handier form $C = \frac{159{,}000}{fX_C}$, where X_C is the capacitive reactance in ohms.

As you know, the larger the condenser, the lower the reactance, hence the greater the current flow for a fixed voltage. This means it is possible to

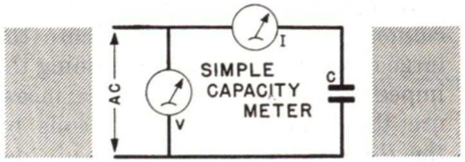

FIG. 26. Circuit for solid-dielectric condensers. They must be in good condition or the current meter can be ruined.

make a simple capacity meter with a basic circuit like that in Fig. 26. Using a fixed frequency and a fixed applied voltage, the current meter scale can be calibrated directly in terms of capacity. Shunts can be used to give different current ranges and extend the capacity range. However, the larger the condenser the lower the reactance, and, hence, the higher the current. This means the condenser size range is limited by the current range, and too large a condenser can cause the meter to be ruined by excess current. A shorted condenser used in this circuit will also ruin the meter. All condensers must first be checked with an ohmmeter to prevent such damage.

You can also measure condenser capacity with the comparison circuit shown in Fig. 27, which requires a vacuum tube voltmeter and a condenser C_S of known capacity. You compare the voltages across the two condensers. As you know, the capacitive reactance increases as the capacity is decreased. Since the voltage drop depends on the reactance, this means the larger voltage drop will appear across the smaller condenser. In other words, the voltage across each condenser is inversely proportional to its capacity.

Therefore, you can say that the ratio of the voltage across the known condenser to that across the unknown condenser equals the ratio of the capacity of the unknown to that of the known condenser. Putting this in a formula, $\frac{V_S}{V_X} = \frac{C_X}{C_S}$ or $C_X = \frac{C_S V_S}{V_X}$. Thus, to find the capacity of the unknown condenser, multiply the capacity of the known condenser by the voltage across it, then divide this product by the voltage across the unknown condenser. The answer is the capacity of the unknown condenser in the same units as the known condenser (usually in microfarads).

If C_S is adjusted so the two voltages are equal, then the capacities are equal. Thus, if you use a calibrated variable condenser at C_S, you can make the voltages equal (so C_S equals C_X) and read the value of C_X directly from the calibration of C_S.

A vacuum tube voltmeter should be used for making measurements—unless the capacities are quite large and

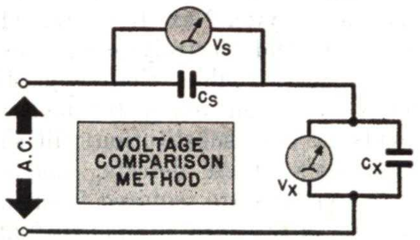

FIG. 27. The comparison method for condensers.

the test frequency is lower than 10 kc., when an ordinary copper-oxide rectifier type meter can be used. If the resistance of the meter is many times higher than the reactance of the condensers, one meter will suffice. But if the meter has such low resistance that it may affect the results, two identical meters should be used.

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ELECTROLYTIC CONDENSERS

The capacity of an electrolytic condenser should be measured with a d.c. voltage applied, because practically all electrolytics need a d.c. voltage to keep the film formed on the anode of the condenser. If an a.c. voltage of more than 3 or 4 volts is applied by itself, the condenser may be ruined. Also, the condenser power factor must usually be taken into consideration, since in

The line V_X represents the true voltage across the condenser reactance. Measure the length of this line, convert it into volts, and divide the voltage thus found by the actual current flow in the circuit (which is equal to voltage V_2 divided by R in ohms). The result is the condenser reactance, which you can readily convert to capacity by using the reactance formula.

Power Factor. The power factor is found by dividing the resistance of a

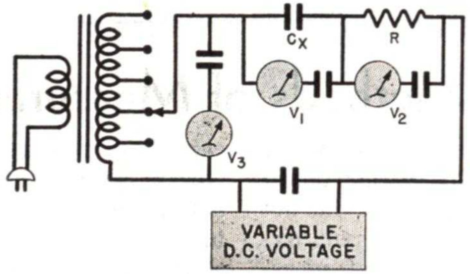

FIG. 28. The polarizing and testing circuit for electrolytics.

electrolytics the series resistance is relatively high.

Fig. 28 shows a circuit for checking an electrolytic. The three-voltage method is used. Since the voltmeters must read a.c. only, they are isolated by blocking condensers.

First, adjust the d.c. voltage to equal some value higher than the peak of the a.c. to be applied. This value plus the applied a.c. peak value must be below the working voltage rating of the condenser. After waiting a reasonable length of time for the d.c. to form the condenser, apply an a.c. voltage from the transformer. (This a.c. voltage must not exceed the d.c. voltage.) Now, measure voltages V_1, V_2 and V_3. Next, construct the triangle shown in Fig. 29 by the same method used in Fig. 24, using V_2 as the horizontal reference vector. Finally, drop a vertical line from the point P to form the line V_X, and extend the line V_2 to form V_R.

part by its impedance. This result is multiplied by 100 to express the power factor as a percentage.

A resistor has a power factor of 1, or 100%, because the resistance is equal to the impedance. On the other hand, a perfect coil or a perfect condenser should have zero resistance and thus zero power factor. Therefore, a coil or condenser with high power factor has considerable series resistance, and so will not act as much like a perfect inductance or perfect capacitance as one with a lower power factor.

After making the triangles shown in Fig. 29, you can determine the power

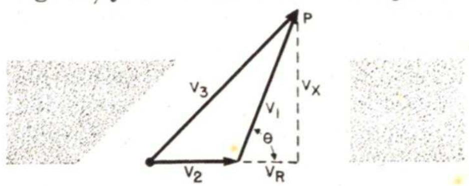

FIG. 29. The three-voltage triangle for electrolytics.

factor of the condenser by measuring line V_R (which represents the voltage drop across the condenser resistance), then dividing this amount by voltage V_1. Multiply by 100 to give the power factor as a percentage. The smaller the power factor, of course, the better the condenser. Measured on 60-cycle a.c., a good electrolytic should have a power factor of about 6%. A percentage above 25% or 30% shows the condenser is poor.

Another point of interest is the Q of the condenser. The larger the Q factor, the better the condenser. This factor may be obtained by dividing the value of V_X by the value of V_R. If angle θ is close to 90°, the Q factor is approximately equal to one, divided by the power factor.

The circuit in Fig. 28 can be used also to measure the capacity of solid-dielectric condensers. To do so, short-circuit the d.c. power pack terminals and make measurements with a.c. only.

Resonance Methods of Measuring L and C

Most of the circuits discussed so far are satisfactory for measuring power supply and audio components but not always reliable at r.f. Resonant circuits are usually better for r.f. measurements, both because they measure small inductances and capacities accurately, and because these measurements can be made regardless of the a.c. resistance or distributed capacity of the device.

In general, to make a resonant circuit measurement, you insert the inductance or capacity to be measured in a circuit that you tune to resonance at a known frequency. Then, since you know the values of the other circuit components, the value of the inductance or capacity under test may be easily determined. Either a series or a parallel resonant test circuit may be used. In a series resonant circuit, a maximum current flow through the circuit or a maximum voltage across one of the parts will show when you reach resonance. In a parallel resonant circuit, a maximum voltage across the circuit, maximum circulating current, or minimum line current will all indicate resonance.

To set up one of these measuring circuits, you need: a signal source capable of delivering about 5 watts of power, with a calibrated frequency output; some means of making measurements at radio frequencies (such as a thermocouple ammeter or an r.f. type vacuum tube voltmeter); and either a calibrated precision condenser or a known inductance. For resistance measurements, a variable resistor calibrated for r.f. will be necessary.

Fig. 30 shows two typical circuits. In Fig. 30A, you know you have reached resonance when the circulating current (measured by the thermocouple type meter) is at a maximum. The indicator in Fig. 30B is a v.t.v.m. which will show a maximum voltage across the condenser at resonance.

In both circuits, the coupling to the oscillator is adjusted to the minimum value that will give a reasonable meter reading. Very frequently an electrostatic shield S (shown by dotted lines) is used between the link coil and the coil in the resonant circuit to eliminate capacity coupling effects.

CAPACITY MEASUREMENTS

Suppose coil L is a known inductance. You can then measure capacity by inserting the unknown condenser in place of condenser C_S and adjusting the frequency of the oscillator until resonance is indicated by a maximum meter reading. The resistor R should be adjusted to zero resistance if the circuit in Fig. 30A is used.

Knowing the frequency and the inductance, you can determine the condenser capacity from the fact that, at resonance, the capacitive reactance equals the inductive reactance. This gives you a formula $C = \frac{25{,}330}{f^2L}$ (where C is the unknown capacity in microfarads, f is the frequency in kilocycles, and L is the inductance in microhenrys) from which you can calculate the unknown capacity.

In this method the a.c. resistance has no effect (because you use a reactance balance, not an impedance balance), and the accuracy depends entirely upon the accuracy with which the inductance and frequency are known. Even the meter accuracy does not matter, since you use it only to indicate a maximum. However, in Fig. 30B, the input capacity of the v.t.v.m. is included in the calculated value. This capacity is small in a well-designed unit, but the measurement is in error by this amount. If you are doubtful about this capacity, use the circuit in Fig. 30A.

If you have a calibrated condenser instead of a known inductance, you can use any coil that will give resonance and find the unknown capacity by substitution, provided the unknown capacity is within the range of the known capacity. First, put the unknown condenser in place of C_S and adjust the oscillator frequency until resonance is indicated. Then replace the unknown condenser with the standard calibrated condenser and adjust the latter until resonance is again indicated, using the same coil and the same frequency. The capacity of the unknown condenser can now be read directly from the scale of the calibrated condenser. We do not need to know the frequency nor the inductance and need make no calculation. Even the v.t.v.m. input capacity will not matter, since it will be present in both cases. Only the accuracy of the standard condenser determines the accuracy of the result, so this method can be very precise.

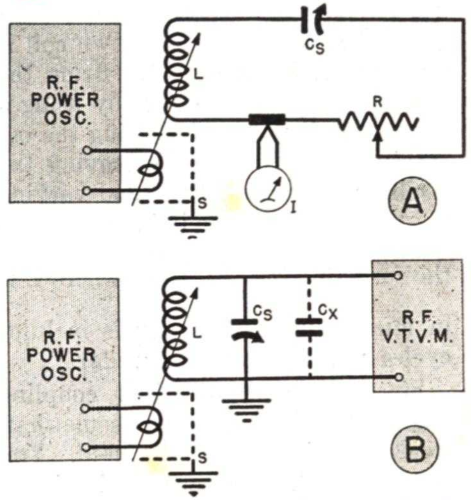

FIG. 30. Resonance methods for measuring inductance and capacity.

Another method of using a calibrated condenser is particularly valuable where the unknown condenser is very small. Leave the calibrated condenser in the circuit and adjust the frequency of the oscillator so that resonance will be obtained with nearly maximum capacity of C_S. Call this C_S value C_1. Next, shunt condenser C_S with the unknown capacity C_X, as in Fig. 30B. This increases the capacity of the circuit, so reduce the value of C_S until resonance is again obtained with the same frequency. Call this value C_2, and find the value of the unknown condenser C_X by subtracting C_2 from C_1. In other words, the capacity of the unknown condenser is

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equal to the difference in the two values of the standard condenser. If a vernier (a geared tuning arrangement, or a calibrated trimmer) is used on the standard condenser C_S, you can measure values as low as 2 micro-microfarads accurately by this method.

INDUCTANCE MEASUREMENTS

Either of the circuits in Fig. 30 can be used to measure inductance if you use a standard condenser and set resistor R at zero. The unknown coil is used as the inductance L. Bring the circuit to resonance, either by using a fixed capacity C_S and varying the oscillator frequency, or by leaving the oscillator frequency fixed and varying C_S, then calculate the inductance from the formula: $L = \frac{25{,}330}{f^2C}$ (where L is in microhenrys, frequency is in kilocycles and C is in microfarads).

Since the oscillator link coupling may affect the inductance somewhat, weak coupling should be used. You can easily tell when the coupling is too tight, because you will get a double resonant hump (two maximum peaks) rather than a single sharp peak indication on your meter. Again, the a.c. resistance has no effect; the accuracy of the measurement depends only on the accuracy with which the capacity and the frequency are known.

COIL A.C. RESISTANCE

Almost always, the a.c. resistance in a tuned circuit will be in the coil. You can neglect the resistance in the average tuning condenser.

You can use the circuit shown in Fig. 30A to measure the coil resistance. First, set resistor R to zero, bring the circuit to resonance and note the current reading on the meter. Then adjust resistor R to a value which reduces the current meter reading to one-half its first reading. This value of R is equal to the a.c. resistance of the coil.

You can easily see why. At resonance, the coil inductive reactance and the capacitive reactance cancel each other, and the circuit current is determined only by the source voltage and the a.c. resistance. When resistor R is increased to a value that cuts the current in half, the resistance in the circuit must have doubled, because you have not changed the source voltage. Therefore, this value of resistor R is equal to the a.c. resistance of the coil. Of course, this method requires that resistor R be variable and be calibrated at the frequency used in making the measurement.

If a variable resistor is not available, you can use a fixed resistor to measure the coil resistance. First measure the current flow with the resistance out of the circuit. Call this I_1. Then, insert a fixed resistor R in the circuit, re-measure the current and call the new reading I_2. The a.c. resistance will be:

$$R_{AC} = \frac{I_2R}{I_1 - I_2}.$$

The fixed resistor should have a value reasonably close to the expected coil resistance, which may range from a fraction of an ohm to 10 or 15 ohms. If it is too large, I_2 will become a very small reading, difficult to determine accurately on the meter scale.

COIL Q FACTOR

As you know, the Q factor of the coil is equal to its reactance divided by its a.c. resistance. If you know the inductance, you can compute the reactance ($X_L = 6.28fL$), find the resistance by one of the methods just described, and so find the Q of the coil at that particular frequency.

You can also find the Q of the coil

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with the circuit shown in Fig. 31. You do not need to know the inductance or resistance of the coil, nor do you need a calibrated condenser. This circuit works on the principle of resonant voltage step-up, using the fact that, at resonance, the voltage across the condenser or the coil equals Q times the source voltage. Thus, you can divide the voltage across the condenser by the source voltage and obtain the Q of the circuit—which is the coil Q when the resistance is all in the coil.

You can easily measure the voltage across the condenser with an r.f.

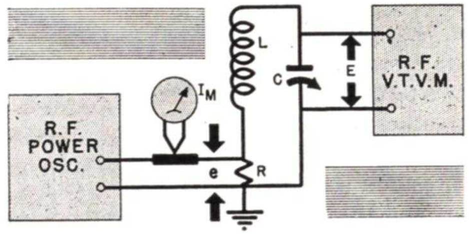

FIG. 31. A circuit for determining Q.

vacuum tube voltmeter, but measuring the source voltage in the resonant circuit is more difficult. The best way is to insert a known small resistance in the resonant circuit and use the voltage drop across it as the source voltage (Fig. 31). Resistor R has very low resistance (a fraction of an ohm), which is only a fraction of the expected coil resistance value. By measuring the current flow from the oscillator through R with the meter I_M, you can find e, which equals $I_M \times R$.

Tune the circuit to a maximum reading on the v.t.v.m., divide this voltage by e, and you have the Q of the circuit. Although this does not give the a.c. resistance or coil reactance, it does give you a way to compare coils for merit. If you know the reactance or the r.f. resistance, you can find the other from $Q = \frac{X_L}{R}$. Of course, the circuit resistance found from this formula includes the resistance of R, but this is usually small enough to neglect. If you wish to be very accurate, you can subtract it from the total resistance.

Of course, the reactance and a.c. resistance both vary with frequency, so the Q found holds good only near the frequency used. If the Q at some other frequency (or over a band of frequencies) is required, then you will have to tune the oscillator to these other frequencies, retune for resonance, and divide the new value of E by the new e to get the Q at these points.

DISTRIBUTED CAPACITY

Occasionally you may want to know the distributed capacity between the turns of a coil. You can measure this with either of the circuits in Fig. 30. First, tune the circuit to resonance at some frequency that uses near maximum capacity of condenser C_S. Call this capacity C_1. Now, without changing the r.f. oscillator frequency setting, adjust C_S to tune the circuit to the second harmonic of the oscillator. Record this value of C_S (which will be about one-quarter the first value) as C_2. The distributed capacity of the coil, C_0, equals $\frac{C_1 - 4C_2}{3}$.

Bridge Measurements

The bridge circuit is the most widely used means of measuring inductance and capacity values. It has the advantage of being a ratio device, so that the values of parts far different from the standard can be checked. Just a few standard parts permit a very wide range of measurement. Let's see how these circuits work.

THE WHEATSTONE BRIDGE

You met the basic bridge circuit earlier in this Lesson. Essentially, it is a connection of four resistors, with a voltage supplied to two terminals and a meter between the other two terminals, as in Fig. 32. To see how the circuit works, let us presume that R_X is an unknown resistor, and that R_3 is adjusted until a value is found that makes the meter read zero.

The fact that the meter reads zero means that points B and C are at the same potential. Tracing the circuit,

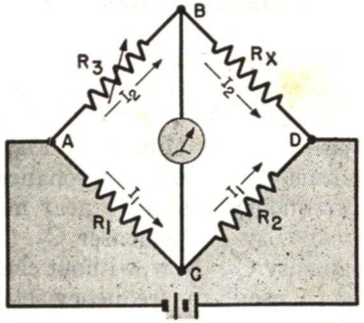

FIG. 32. The basic Wheatstone resistance bridge.

you will see that this means the voltage drop across R_1 equals that across R_3, and the drop across R_X equals that across R_2. In other words, assuming that a current I_1 flows through resistors R_1 and R_2, and that another current I_2 flows through R_3 and R_X, the circuit is adjusted in such a way that:

$$R_X \times I_2 = R_2 \times I_1$$

and

$$R_3 \times I_2 = R_1 \times I_1$$

If you divide the upper equation by the lower equation, the currents will cancel and you will have:

$$\frac{R_X}{R_3} = \frac{R_2}{R_1}$$

This says that the ratio of R_X to R_3 is the same as the ratio of R_2 to R_1. Carrying this a step further, you have:

$$R_X = \frac{R_2}{R_1} \times R_3.$$

This is a very important equation. It shows that if you make R_1 equal to R_2, then R_X will be equal to the value of R_3 that will bring the bridge into balance (give zero meter reading). But if R_1 and R_2 are not equal, this equation further shows that R_X will be equal to the *ratio* of R_2 to R_1, multiplied by the value of R_3 that balances the bridge. This means that even if resistor R_3 has only a limited range of variation, you can still measure an unknown resistor R_X of almost any value merely by choosing the proper ratio between resistors R_1 and R_2. This, of course, gives you a highly flexible measuring circuit.

In practical bridge circuits, resistors R_1 and R_2 are made so that they can be varied in decimal ratios to each other—such as 1 to 1, 1 to 10, 1 to 100, 1 to 1000, or 1000 to 1, 100 to 1, or 10 to 1. Usually, R_1 is an accurate fixed resistor, and R_2 a series of fixed resistors arranged with a switch so the ratio can be varied in steps. Then the only continuously variable resistor will be R_3, and even for this, fixed resistors in a decade box arrangement may be used.

As shown schematically in Fig. 33, a decade resistance box is a series of accurate resistances connected to contacts. Various resistances can be obtained by switching to various contacts. The name comes from the fact that each switch section has ten contacts, so there are ten steps (decade means a group of ten) in each section.

With the particular arrangement shown, any resistance between 0 ohms and 1110 ohms can be obtained in 1-ohm steps. (The switches are shown set in the 0-ohm position.) If, for example, switch SW_1 is moved over to contact 4, there will be 4 ohms resistance between terminal A and terminal B. If SW_2 is then set to contact 6, 60 ohms will be added to the 4 ohms and you will have 64 ohms. If SW_3 is moved to contact 8, 800 ohms will be added in the circuit; you would then have a total of 864 ohms, etc.

The values of the resistances need not be 1, 10, and 100 ohms each; they can be small fractions of an ohm or much larger values, depending on the design of the decade box.

In using a bridge, the ratio of $R_2 \div R_1$ is adjusted to a likely value (R_X may or may not be approximately known) and R_3 is adjusted to make the meter read zero. If the bridge cannot be balanced, other ratios are tried until the zero reading is found. Then R_X equals the $R_2 \div R_1$ ratio multiplied by R_3.

Of course, the meter will read until the bridge is balanced. Since the amount of meter current depends on the amount of unbalance, it may be large if the bridge is far from balance. Further, the direction of current flow through the meter depends on whether the unknown is larger or smaller than the ratio times R_3.

To let the meter pointer swing in either direction, the meter springs are adjusted so zero is in the center of the scale. By noting which way the meter deflects, you can tell what adjustment is needed to balance the bridge. Thus, a deflection to the left may mean an increase in R_3 is needed for a balance, and a deflection to the right may mean R_3 should be decreased. It may be the other way around, depending on how

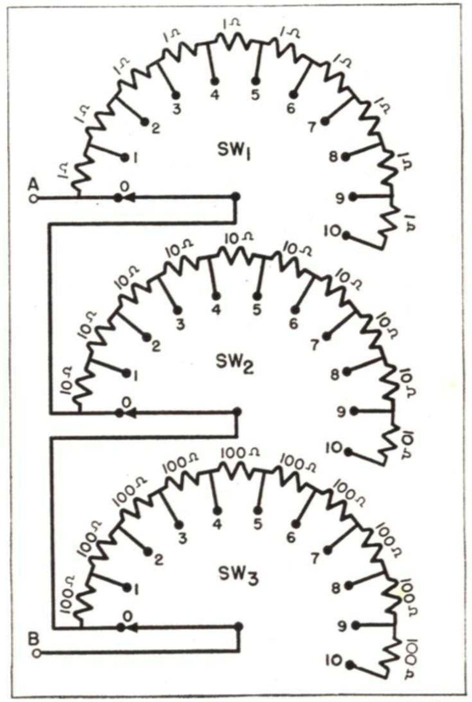

FIG. 33. A decade box.

the battery is connected to the bridge.

To prevent ruining the meter with excess currents, a switch like SW in Fig. 34 is usually used. This is a three-position switch that can be thrown to the right or the left from its normal resting position. Position 1 is the normal position and opens the meter circuit. (A spring returns the switch to this position when it is not held by the operator.) In making readings, the switch is first thrown to position 2, closing the meter circuit and connecting a shunt across the meter at the same time. This makes the meter insensitive and protects it from excess current. The bridge is adjusted until

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the meter shows little or no deflection, then the switch is moved to position 3, which places the sensitive meter directly in the circuit, and a final balance is found.

Until the bridge is almost balanced, the switch is closed only long enough

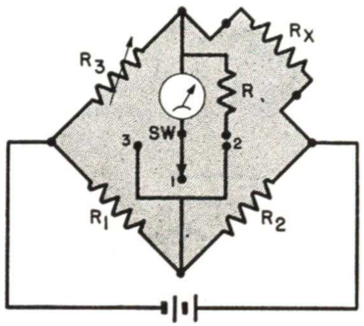

FIG. 34. For meter protection, switch position 2 is used until the bridge is nearly balanced.

to see whether the meter pointer moves rapidly away from zero. Then, as the balance point is neared, the current drops so that a reading can be taken safely. Even so, the switch is allowed to return to position 1 while any adjustment is made.

A.C. BRIDGES

It is not necessary to use a d.c. power supply with a bridge. You can use an a.c., a.f., or r.f. voltage if you wish—but you must use an indicating device suitable for the kind of voltage used. For an audio voltage, an a.c. meter or a pair of headphones may be used as shown in Fig. 35. Balance will be shown by a zero meter reading or minimum sound in the phones. R.F. voltages require a v.t.v.m. as the indicator.

An a.c. bridge is more generally useful than a d.c. bridge, for we can measure coils and condensers as well as resistors with it. The a.c. bridge balances when the *impedances* of the arms are in the proper ratios.

You might think that you have to use coils in all four arms of the bridge to obtain an inductance balance, and capacities in all arms for a capacity balance. The fact is, the ratio arms R_1 and R_2 can be resistances as long as they do not have appreciable inductance or capacity. Then a standard inductance can be used in place of R_3 for inductance measurements, or a standard capacity in place of R_3 for capacity measurements.

Capacity Bridge. The bridge for capacity measurements shown in Fig. 36A looks just like the resistance bridge of Fig. 35 except for the substitution of the two condensers. This bridge will balance when the impedances of the condensers have the relationship $Z_{CX} = \frac{R_2}{R_1} \times Z_{CS}$.

We can find the capacity of C_X if we assume that the impedance of a condenser is approximately the same as its reactance (for air- or solid-dielectric types the resistance is negligible) and

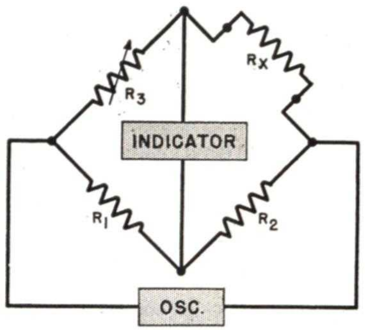

FIG. 35. This basic a.c. bridge is just like the d.c. bridge except for a change in the voltage source and the indicator.

remember that the reactance is inversely proportional to the capacity $\left(X_C = \frac{1}{6.28fC}\right)$.

Substituting this relationship in the above formula and simplifying, you get $C_X = \frac{R_1}{R_2} \times C_S$. Notice that this

capacity formula has *just the opposite ratio of resistances* from the formula used with the resistance bridge.

Inductance Bridge. On the other hand, you should use the *same* resistance ratio for the inductance bridge

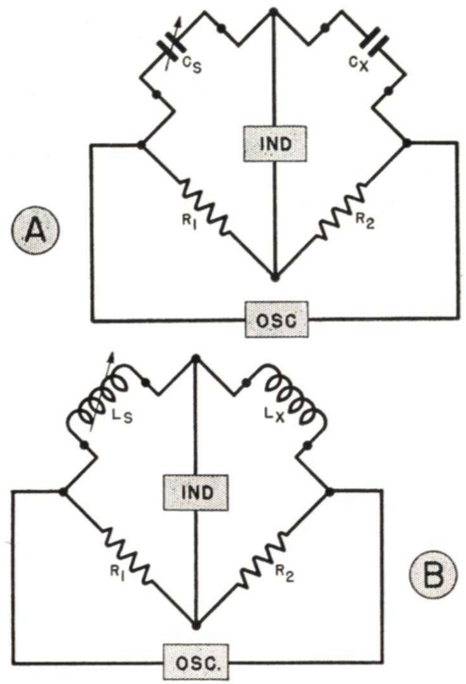

FIG. 36. The bridge at A is a capacity bridge, while B shows an inductance bridge.

(Fig. 36B) as for a resistance bridge, because inductive reactance is proportional to inductance. The formula for this bridge is: $L_X = \frac{R_2}{R_1} \times L_S$.

Wagner Ground. When you measure high-impedance parts (small-capacity condensers or high-inductance coils), particularly at high frequencies, you may find that body capacity unbalances the bridge. For example, putting on the phones used as an indicator—or even bringing your hand close to the bridge—may change your readings. Grounding the bridge directly would solve this difficulty, but would also present us with another one just as bad, for the stray capacities C_1 and C_2 shown in Fig. 37 would then shunt the ratio arms and would themselves determine the ratio setting.

The best solution is to balance the entire bridge with respect to ground. One way to do so is to use a system known as a Wagner ground, shown in Fig. 37. A low-resistance potentiometer R_3 is connected across the bridge and the variable arm is grounded. As you see, this puts a low-resistance shunt across C_1 and C_2. To operate a bridge using this ground, first balance the bridge in the usual manner as well as possible. Then, throw switch SW to the ground position and adjust R_3 to give a minimum indication. (Notice that grounding one terminal of the indicator through switch SW makes another bridge of R_1, R_2 and the two sections of R_3, since this connects the indicator between C and ground, and

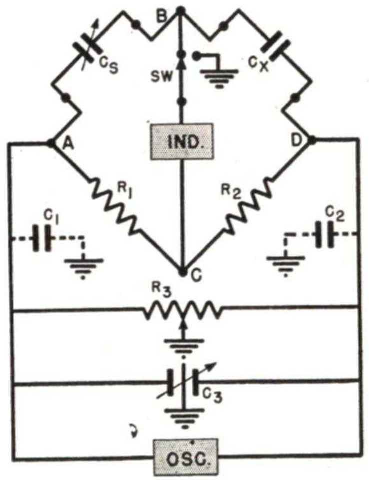

FIG. 37. Balancing to ground to eliminate body capacity effects.

through the ground to the arm of R_3.)

The bridge is balanced with respect to ground when a minimum indication is obtained. You should then throw the switch back to its normal position and readjust the bridge to give a minimum

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indication. If necessary, repeat this process until further adjustments cause no upset of the bridge.

Since the trouble is caused by capacity to ground, the resistance of R_3 may be too high to permit a fine bal-

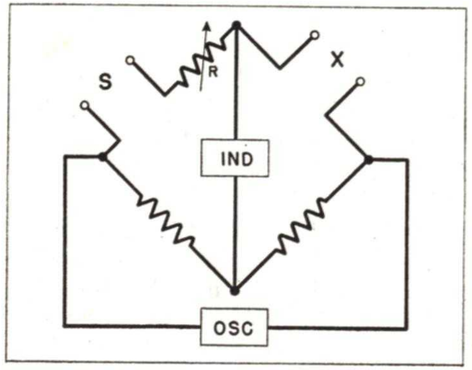

FIG. 38. Using R permits the bridge to be balanced for the resistance of the unknown part while its reactance is balanced by that of the standard part. This gives a direct measure of the a.c. resistance of the unknown part, and permits the calculation of the Q.

ance at the higher radio frequencies. For high-frequency work, some bridges use the split-stator condenser C_3 shown in Fig. 37. This is a condenser with two stator sections and a single common rotor section; as the condenser is rotated, the capacity of one section increases while that of the other decreases. Its capacity can thus be varied to make the capacitive reactance between A and ground and that between D and ground have the same ratio as the $R_1 \div R_2$ ratio, thus balancing the bridge with respect to ground. The balancing procedure is like that used with the Wagner ground—except that you vary C_3 instead of R_3.

IMPROVED BRIDGE CIRCUITS

The basic bridge we have discussed so far is excellent if you can neglect resistance in the coil or in the condenser being checked and the resistance in your standard. But a zero current indication can be obtained only if the *impedances* of the arms are exactly equal; if the unknown has appreciable resistance as well as reactance, you can get a *minimum indication* but not a true *zero indication*. This causes some error in adjusting the bridge. However, a simple means can be used to get a true zero balance and, at the same time, determine the Q factor of the coil or condenser.

Usually the standard coil or condenser is chosen to have very low resistance, so if a resistance unbalance exists, it will usually be the fault of the unknown coil or condenser. As shown in Fig. 38, you need only add resistance in series with the standard coil or condenser to bring the bridge back into balance. To use this circuit, insert the coil or condenser standard and the unknown as indicated, and adjust the standard or the ratio arms to give a minimum indication. Then, adjust R for a further reduction. Repeat the standard and R adjustments until the indication cannot be reduced further. When the *least possible* signal is

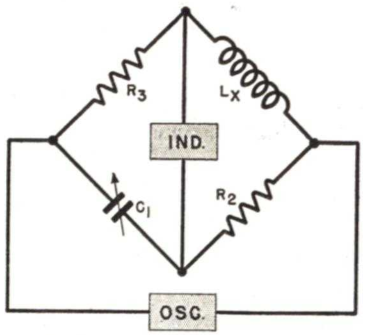

FIG. 39. This bridge balances a capacity against an inductance.

heard or indicated, the reactive components of the standard and unknown are balanced, and so are the resistive components of the unknown and resistor R. Multiplying the value of resistor R by the bridge ratio will give

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the amount of resistance in the unknown part.

Thus you can determine the capacity or inductance and the a.c. resistance of the unknown part at the same time. If you want to find the Q factor of an

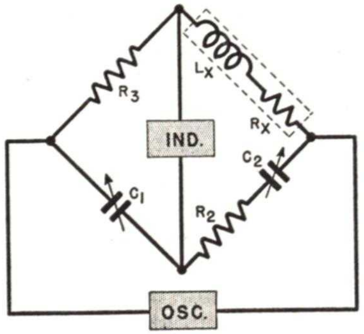

FIG. 40. The Owen bridge.

inductance, find the inductive reactance from the formula $X_L = 6.28fL$, then divide this reactance by the resistance. Similarly, you can find the Q of a condenser by dividing the reactance by the a.c. resistance. However, the reactance of the condenser is

$$X_C = \frac{1}{6.28fC}, \text{ so } Q_C = \frac{X_C}{R} = \frac{1}{6.28fCR}.$$

Since the power factor is approximately $\frac{1}{Q}$ for low power factor condensers, the power factor is 6.28fCR.

Comparing L with C. In the basic bridges covered so far, coils have been compared with coils, and condensers with condensers. There are many variations of these bridges, found mostly in laboratories. Some have resonant circuits in their arms, others are designed for certain special purposes.

Another type, which balances a condenser against a coil, is very useful. A basic form of this bridge, using a standard condenser (which is more likely to be available than a standard coil) is shown in Fig. 39. Since the capacitive reactance is opposite in phase to the coil reactance, the balancing condenser must be in the position shown. The value of

$$L_X = R_2 R_3 C_1.$$

Fig. 40 shows the Owen bridge, a more common form of this circuit, which also takes the a.c. resistance of the coil into account. The capacity C_2 is used to balance the coil resistance R_X. The a.c. resistance of the coil is found from the formula

$$R_X = \frac{C_1}{C_2} \times R_3$$

and the inductance is found by the formula in the preceding paragraph.

This bridge is easily converted into a standard capacity bridge, so it can be used to check both inductance and capacity, using only a standard condenser.

Bridge Limitations. Most a.c. bridges work over a limited audio to low r.f. range. If the frequency is increased, complete shielding of each element becomes necessary, and many precautions must be observed, to prevent stray fields and coupling between parts from upsetting results. Although high-frequency r.f. bridges are available, they are costly and are found only in large laboratories. For ordinary purposes, the resonance method is usually used when very high frequencies are involved.

Frequency Measurements

The accurate measurement of frequency is a subject of considerable importance to a communications man, because a radio transmitter must be kept very near its assigned frequency at all times. The apparatus used for this purpose will be described in detail in a later Lesson. Here we shall show you how primary standards of frequency are established, and describe two instruments that are commonly used to measure radio and audio frequencies.

The number of times an event repeats itself within a specified length of time is its frequency—usually measured in cycles per second. Therefore, the first requirement for accurate measurement of frequency is a highly accurate way to tell time. The fundamental unit of time is determined by the rotation of the earth. By observing the positions of certain stars, astronomers determine this period exactly. From these observations, extremely accurate standard clocks are calibrated. Now if you were to use the output of an oscillator to drive an electric clock, you could compare the time kept by the electric clock with that kept by a standard clock and have a very precise way to measure both the frequency of the oscillator and its ability

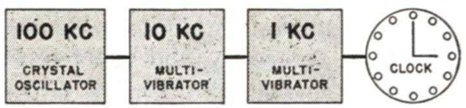

FIG. 41. How an electric clock is run from a crystal oscillator.

to maintain that frequency. You could then use the oscillator output as a standard of frequency.

Primary standards of frequency of this kind are found in the National Bureau of Standards and other large laboratories. They are crystal oscillators, because this type has the greatest frequency stability, and are kept at constant temperatures to make them as stable as possible.

Usually these oscillators produce frequencies of 50 to 100 kilocycles. Either frequency is too high to drive an ordinary clock, so it is stepped down by a chain of multivibrators. (The multivibrator is a circuit that can produce an accurate fraction of a frequency fed into it.) Fig. 41 shows how the crystal oscillator is used to drive a chain of multivibrators that finally produces a signal capable of driving a clock. The clock used follows frequency exactly, so comparing its time with that of a standard clock shows us the frequency of the crystal oscillator and also indicates any variations in this frequency. By making adjustments to keep the clocks together, the output of the oscillator can be used as a frequency standard.

The Multivibrator. This interesting circuit does not "vibrate"—it is an oscillator consisting of a two-stage resistance-coupled amplifier like that shown in Fig. 42. Notice that condenser C_2 provides a feedback path from the plate circuit of the tube VT_2 to the grid circuit of tube VT_1. Each tube reverses phase by 180°, so two tubes produce a 360° reversal. This means the voltage across R_4 is back in phase with the input of VT_1, so this feedback path allows the circuit to oscillate.

By inserting a bias, we can make one tube draw slightly more plate current than the other when the circuit is first turned on. For this explanation, we will assume that VT_1 draws more current than VT_2. The initial rush of current through R_2 produces a voltage pulse across it, with a polarity such that the end of R_2 marked 1 is negative. This pulse passes through C_1 and is developed across R_3, driving the grid of VT_2 negative and so cutting off its plate current. This causes a rapid decrease in the voltage drop across R_4; you can consider this decrease to be a voltage pulse with a polarity such that the end of R_4 marked 3 is less negative (more positive) than normal. This pulse, in turn, passes through the coupling condenser C_2 and is developed across R_1, making the grid of VT_1 positive and so increasing its plate current.

The plate current of VT_1 increases until the tube becomes saturated. When this occurs, the current becomes constant, and so does the voltage drop across R_2. In other words, there is no longer a voltage pulse across R_2 and, naturally, no pulse voltage developed across R_3. With the disappearance of the pulse voltage across R_3, the grid of VT_2 is able to go back to its initial bias. (This does not happen instantaneously, because C_1 has been charged and must discharge through R_3 before the grid of VT_2 can reach its original bias; this, of course, takes a little time.)

As the grid of VT_2 approaches its initial bias, plate current again starts to flow through the tube. This increasing current creates another voltage pulse across R_4. Because the current is increasing, this time the pulse has a polarity such that the end of the resistor marked 3 is negative. This pulse, passing through C_2, drives the grid of VT_1 negative, and stops the flow of plate current through the tube. This causes a voltage pulse across R_2, with a polarity such that point 1 is more positive; passing through C_1, this pulse makes the grid of VT_2 positive, and the current through VT_2 increases.

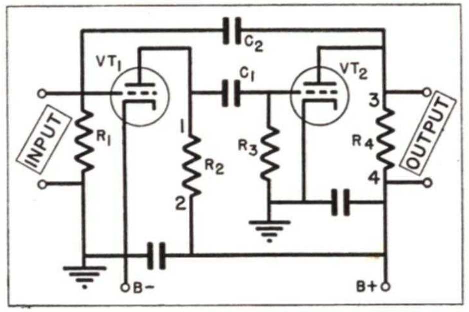

FIG. 42. A multivibrator is a resistance-coupled amplifier that can oscillate.

Now it is the turn of the current through VT_2 to increase until saturation is reached. When the tube does saturate, VT_1 is able to pick up again, while VT_2 shuts off. This process is repeated over and over, with current flowing through first one tube, then the other. The net effect of this action, as far as output is concerned, is that voltage pulses appear across R_4.

The rate at which these pulses occur—that is, the frequency of oscillation of the circuit — depends on the time constants of the C_1-R_3 and C_2-R_1 combinations. As you just learned, C_1 must discharge through R_3 before VT_2 can pick up; similarly, C_2 must discharge through R_1 before VT_1 can pick up. By adjusting the capacities and resistances of these combinations, you can obtain almost any fundamental frequency you want.

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The output of this oscillator is rich in harmonics—in fact, the output wave may be triangular or even square in shape because there are so many.

Although the multivibrator is fairly stable, its frequency can shift somewhat with changes in tube characteristics, operating voltages, etc. However, it will "lock in" with control pulses fed in the input, and will then produce its fundamental just as accurately as the control pulses are maintained. Equally as important—it will lock with a control pulse that is some multiple of its fundamental. For example, a 1-kc. multivibrator can be controlled by a 10-kc. control unit, because it will ignore all pulses in the input except the one it is locked with.

You see, at some time during the cycle of operation the voltage on the grid of VT_1 has such a value that the tube can almost conduct current. Now suppose you feed in a 10-kc. signal across R_1. This signal adds to the voltage already present across R_1. If you adjust the amplitude of this signal carefully, you can make it increase the voltage on the grid of VT_1 just enough to make the tube start conducting a tiny fraction of a second ahead of the time it would have started if the signal had not been fed in. The circuit then proceeds through its normal operating cycle, unaffected by the input voltage, until it reaches the precise point where the input voltage is again able to make VT_1 conduct. Since the fundamental frequency of the circuit is 1 kc., this point will not arrive until 9 cycles of the input signal have passed by, because these intermediate pulses, when added to the voltage across R_1, are not of sufficient amplitude to start tube conduction. However, the feedback voltage is continuously building up, and the tenth cycle of the input signal will make VT_1 conduct again. Thus, the multivibrator locks in step with every tenth cycle of the input frequency, but ignores the cycles in between.

In other words, the oscillation of the vibrator is precisely controlled by the input voltage, which overcomes the tendency of the circuit to wander and shift frequency. Thus, the fundamental and all its harmonic frequencies will be just as accurately controlled as is the input voltage. Further, the circuit can be controlled by frequencies as high as the tenth harmonic of the fundamental. Therefore, you can lock the circuit at the input side with one of its harmonics, but use the fundamental as the output frequency, and so get an output that is any fraction (up to, say, a tenth) of the input frequency.

It is this characteristic that makes the multivibrator useful in the circuit in Fig. 41. The crystal produces a 100-kc. voltage that controls the 10-kc. (fundamental frequency) multivibrator. The 10-kc. multivibrator in turn controls a 1-kc. multivibrator. By bringing out taps from the multivibrators in Fig. 41, you can obtain voltages with frequencies maintained just as accurately as the crystal oscillator frequency itself. If you want still lower frequencies, say for calibrating a device used to measure audio frequencies, simply add one or two more multivibrators to the chain. One additional multivibrator will give a frequency of 100 cycles, two a frequency of 10 cycles.

Because it has so many harmonics, you can obtain from the 10-kc. multivibrator frequencies of 10 kc., 20 kc., 30 kc., etc., all the way up to 1000 kilocycles. Similarly, the 1-kilocycle multivibrator produces 1-kilocycle steps all the way up to 100 kilocycles. If you wish, you can feed these outputs into other multivibrators and so get a large number of extremely accurate frequencies. Then, the output from such a primary frequency standard can be used to calibrate secondary standards.

Measuring Transmitter Frequencies. As we said earlier, the instruments used to measure the frequency of a transmitter will be described in a later Lesson. We might say here, however, that such instruments usually compare the output of a highly accurate frequency standard (generally a crystal oscillator) with the output of the transmitter. Usually this is done by mixing the two frequencies together and measuring the beat frequency produced. Extremely accurate measurements of frequency can be made this way, as you will learn.

Now, let's take a quick look at two instruments commonly used to measure frequency. These devices, though they do not have the extreme accuracy required for the precise control of a transmitter, are nonetheless useful when relatively rough measurements will suffice.

THE WAVEMETER

A very common frequency-indicating device is a wavemeter. This is nothing more than a coil-condenser resonant circuit. Many have some means of indicating when they are tuned to resonance—such as a vacuum tube voltmeter, a thermocouple current meter in series with the resonant circuit, or a lamp (which will burn brightest when resonance is reached).

When the wavemeter has no indicator, you must depend on the meters associated with the source as indicators. Practically all r.f. power oscillators and power amplifiers have plate current meters. When a wavemeter is brought near a resonant circuit and is itself tuned to resonance, it will absorb energy from the source. The plate current rises when this power is being furnished, so the point of maximum rise in plate current is the point of resonance (provided you are not too closely coupled, so as to cause a broad response or stop the oscillator).

To use a wavemeter, bring its coil close to an inductance in the circuit producing the frequency to be checked. If it is physically impossible to do this, feed the output of the circuit into a coil and bring the wavemeter near this coil. Then, vary the tuning condenser dial until resonance is indicated and read the frequency off the dial. You may have to use a calibration chart if the condenser dial is not calibrated directly in frequencies.

Wavemeters will maintain their accuracy of calibration for quite a long time if made from precision parts. However, a wavemeter must be carefully made to be accurate—and even then will not show variations in frequency less than 1% of the fundamental. For this reason, the instrument is used primarily for experimental purposes where an approximate measurement is all that is required.

THE WIEN BRIDGE AS A FREQUENCY INDICATOR

Any resonant bridge circuit can be used like a wavemeter to determine frequencies. For audio frequencies, a bridge called the Wien bridge (which is also very popular for measuring capacities) is particularly useful. Its circuit is shown in Fig. 43.

This bridge can measure frequencies because of the actions of the arms containing the condensers. Notice that C_1 is in shunt with R_3 and C_2 is in series with R_4. As you can see, the impedance between terminals A and C can drop to a very low value at high frequencies because of the drop in reactance of C_1. However, no matter how high the fre-

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quency, the impedance between C and D can never drop below the value of R_4. On the other hand, if the frequency is decreased, the impedance between A and C will never go higher than the value of R_3, but that between C and D can go on up to practically an open circuit.

Therefore, as you move from any one particular frequency in either direction, the reactances of the two arms will behave in different manners. In fact, they act much as a coil and condenser would—therefore, in effect, this is a resonant circuit. We won't go into the engineering behind this bridge, but if resistor R_1 is twice R_2, C_1 equals C_2, and R_3 equals R_4, the frequency of balance of the bridge will be $f = \frac{159{,}000}{RC}$, where f is in cycles, C is in microfarads and R is in ohms. In this case, R is the value of either R_3 or R_4, and C is the value of either of the condensers.

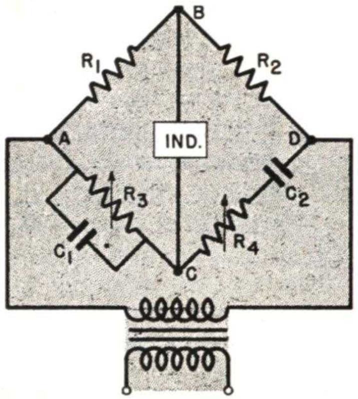

FIG. 43. The Wien bridge used as a frequency indicator.

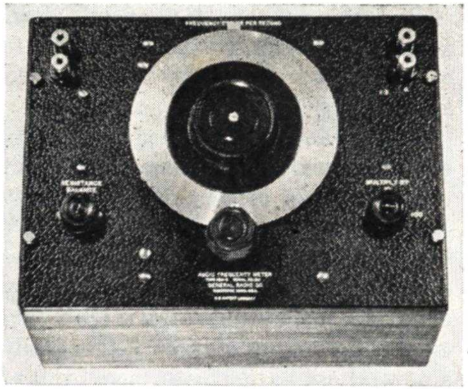
Courtesy General Radio

FIG. 44. A typical laboratory type frequency meter using the Wien bridge.

By varying the resistances of R_3 and R_4 (but keeping them equal), or by using different sizes of condensers (but keeping them equal also), we can change the frequency to which the bridge balances. Thus, we can use the bridge to determine the frequency of the source connected to it, provided we know the capacity of the condensers and the value of the resistors. A typical a.f. bridge is shown in Fig. 44. The main dial varies the resistors, which are ganged together.

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Lesson Questions

Be sure to number your Answer Sheet 38RC.

Place your Student Number on *every* Answer Sheet.

Most students want to know their grade as soon as possible, so they mail their set of answers immediately. Others, knowing they will finish the next Lesson within a few days, send in two sets of answers at a time. Either practice is acceptable to us. However, don't hold your answers too long; you may lose them. Don't hold answers to send in more than two sets at a time or you may run out of Lessons before new ones can reach you.

1. Why is a v.t.v.m. better than a D'Arsonval type voltmeter for making measurements in high-resistance circuits?
2. Draw a simple resistance bridge circuit.
3. If the peak value of a half-wave rectified sine wave is 100, what is its r.m.s. value?
4. When measuring the inductance of an iron-core coil, what value of polarizing (d.c.) current should flow through it?
5. Which of the following condensers requires a polarizing voltage when checking the capacity: *1, air dielectric; 2, paper; 3, ceramic; 4, electrolytic; 5, mica?*
6. What property of an electrolytic condenser is usually of interest, in addition to its capacity and working voltage?
7. When finding the Q using the circuit of Fig. 31, what basic principle is being used in the measurement?
8. Using the decade box of Fig. 33, to which contacts would you set switches SW_1, SW_2, and SW_3 so that you would have 471 ohms between terminals A and B?
9. What is the device called that is used to derive a standard frequency of 10 kc. from a standard frequency oscillator operating on 100 kc.?
10. Suppose you are using a wavemeter, consisting of a coil and a condenser, which has no built-in indicator. If this wavemeter is brought near an oscillator tank circuit, what indication will be obtained on the oscillator plate current meter when the wavemeter is tuned to resonance?

MAKE BELIEVE IT'S TRUE

A young man once asked a successful friend to state just one rule for success. "*Look as though you have already succeeded,*" the friend advised. Following this rule eventually made this man president of a great bank in New York City.

As Shakespeare expresses it: "*Assume a virtue if you have it not.*" Dress like a successful man, act like a successful man. Be successful in all your thoughts, and you will be successful in the world as well.

David V. Bush states this same thought in terms of radio: "*If we think poverty thoughts, we become the sending and receiving station for poverty thoughts. We send out a 'poverty' mental wireless, and it reaches the consciousness of some poverty-stricken 'receiver.' We get what we think. If we are going to be timid, selfish, penurious, and picayunish in our thinking, these thought waves will go forth until they come to a mental receiving station of the same caliber. 'Birds of a feather flock together,' and minds of like thinking are attracted one to the other.*"

Once you learn that you have a legitimate control over your own affairs, that you have the right to win, *you will win.*

J. E. SMITH

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