the GENERAL RADIO Experimenter

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VOLUME 32 No. 4 SEPTEMBER, 1957

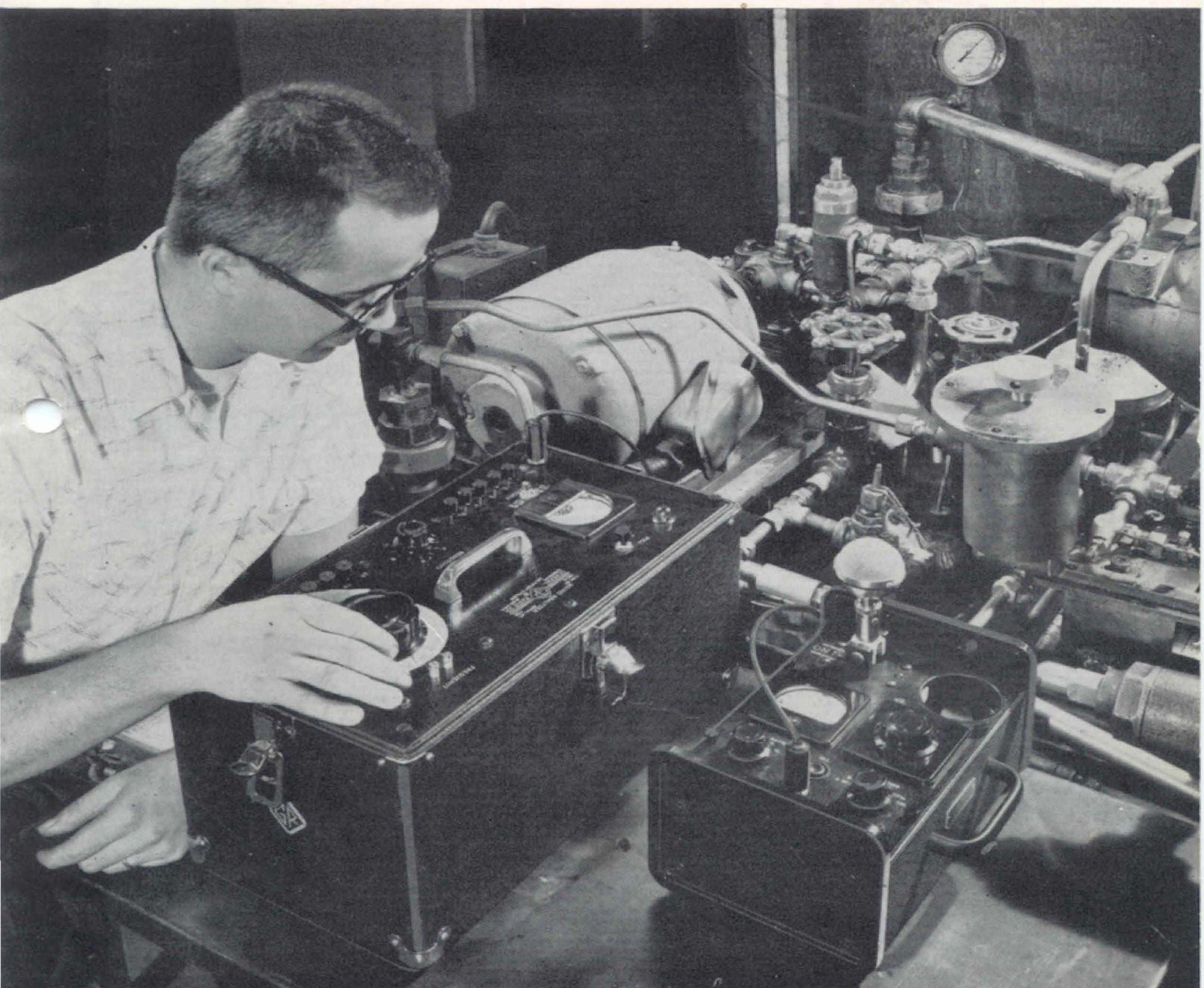

Photo Courtesy The Oilgear Company

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Phase Angle of Potentiometers
Representative for Germany
UL-Approved Variacs®

the GENERAL RADIO Experimenter

Published Monthly by the General Radio Company

VOLUME 32 · NUMBER 4 **SEPTEMBER, 1957**

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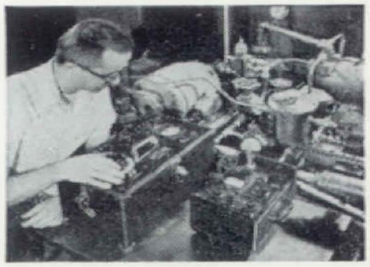


At the Oilgear laboratories in Milwaukee, measurements on fluid-power pumps with the General Radio Sound-Level Meter and Sound Analyzer provide valuable information for setting performance standards, designing better products, and correcting faulty performance.

THE PHASE ANGLE OF POTENTIOMETERS USED AS RHEOSTATS

The phase angle of a variable resistor is nearly always a problem in precision a-c circuitry. It is now becoming increasingly important owing to the widespread use of this type of component in computing and control systems. Investigations of the voltage phase shift in potentiometers used as voltage dividers have been reported in the literature.[1, 2] This article is primarily concerned with "pots" used as rheostats, and, therefore, the phase angle is that of an impedance.

We are interested here only in the small phase angle by which a rheostat differs from a pure resistance. This variation from the ideal, caused by inductance and stray capacitance, is often appreciable at audio frequencies. We are not concerned here with the large phase angles that occur at higher frequencies.

The precise measurement of the phase angle of a resistor at audio frequencies has hitherto been difficult,[3] largely because most audio-frequency bridges use rheostats whose phase angles may be comparable to those which are to be measured. The new General Radio TYPE 1605-A Impedance Comparator[4] makes possible precise yet rapid measurements by comparison with small fixed resistors of negligible phase angle. The desire to explain data taken with this instrument has led to the analyses and calculations which follow.

PHASE ANGLE CALCULATIONS ON RHEOSTATS

Fixed Resistors: Let us consider first the phase angle of a fixed resistor. The familiar equivalent circuit of Figure 2 is valid in all resistors if we consider only small phase angles.

The Q of this circuit is:

$$Q = \omega(L/R - RC) - (\omega^3 L^2 C/R) \quad (1)$$

We will limit ourselves to values of Q less than 0.1, so that we can set:

$$Q = X/R \cong \theta = \tan^{-1}(X/R) \quad (2)$$

where θ is in radians (since tan (.1) = .1003, which is close enough for our calculations). To show that the ω^3 term is negligible, we can express $\omega^3 L^2 C/R$ as $(\omega L/R)^2(\omega RC)$. If ωRC and $\omega L/R$ are each less than 0.1, the cubed term is less than 1/100 of the first-order terms

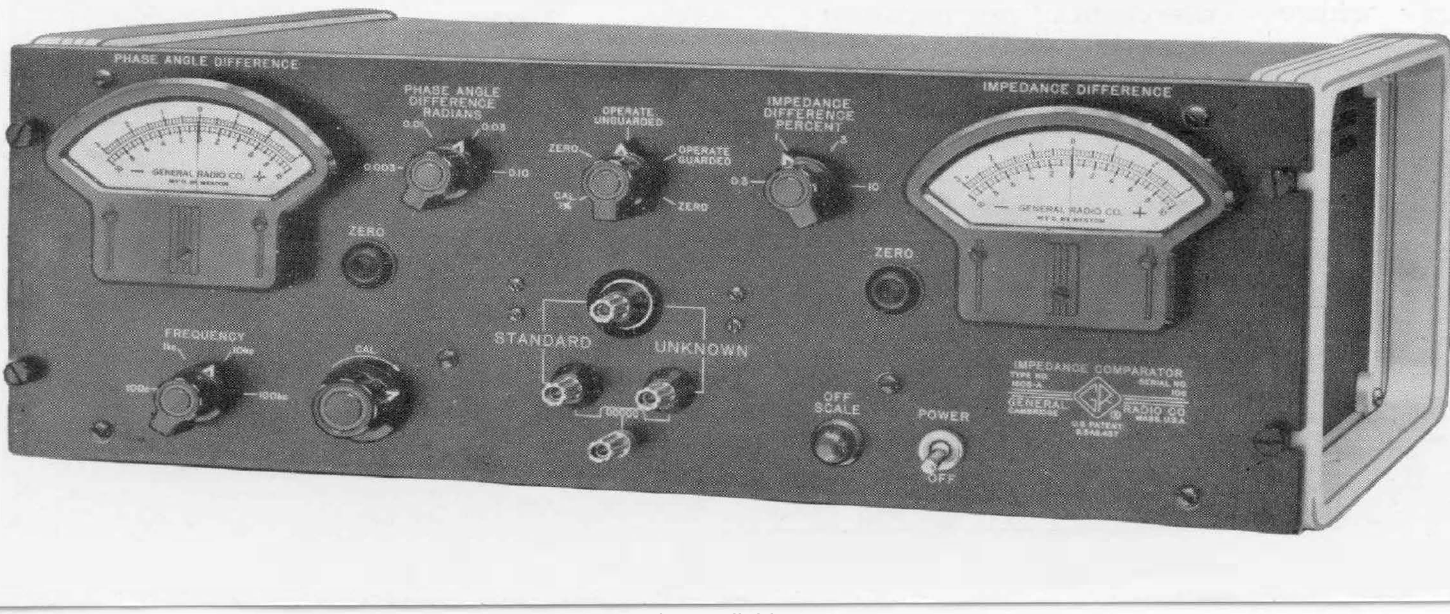
[1] M. H. Hayes and J. L. West, "Potentiometer Characteristics," *Tele-Tech and Electronic Industries*, February, 1955.

[2] "A-C Performance and Phase Compensation of Copper Mandrel Potentiometers," *Helipot Technical Paper*, 4.97.

[3] G. H. Raynor and L. H. Ford, "The A-C Properties of Resistors and Potential Dividers at Power and Audio Frequencies, and their Measurement," *Journal of Scientific Instruments*, 3, 4, 5, May, 1955.

[4] M. C. Holtje and H. P. Hall, "A High-Precision Impedance Comparator," *General Radio Experimenter*, 30, 11, April, 1956.

Figure 1. Panel view of the Type 1605-A Impedance Comparator, used for the measurements described in this article.



and is thus negligible. This would indicate that the effects of inductance can be added to those of capacitance, since the terms resulting from the interaction between the two are negligible for small phase angles. Therefore, we can use the simple expression

$$\theta = Q = \omega [L/R - RC] \qquad (3)$$

for our calculations. Note from this expression that:

(a) Q is proportional to ω, and therefore the frequency of measurement is unimportant, except that it must be chosen to give Q values that are measurable but less than 0.1.

(b) Low-valued resistors are inductive, and high-valued resistors are capacitive. The transition for wire-wound resistors occurs usually between 2000 and 20,000 ohms.

(c) For values of R where both terms are important, it is impossible to measure L and C separately.

Rheostat with Inductance Only

Figure 3 shows a measured curve of Q vs rotation for a 1000-ohm pot (Type 973K). This plot shows that, for most of the range of rotation, Q is constant. This means that the inductance is increasing linearly with rotation. If Q is assumed constant, the equivalent circuit is that of Figure 4, and the expression for Q is:

$$Q = \omega(\alpha L/\alpha R) = \omega L/R \qquad (4)$$

where α = normalized rotation
R = total resistance
L = total inductance

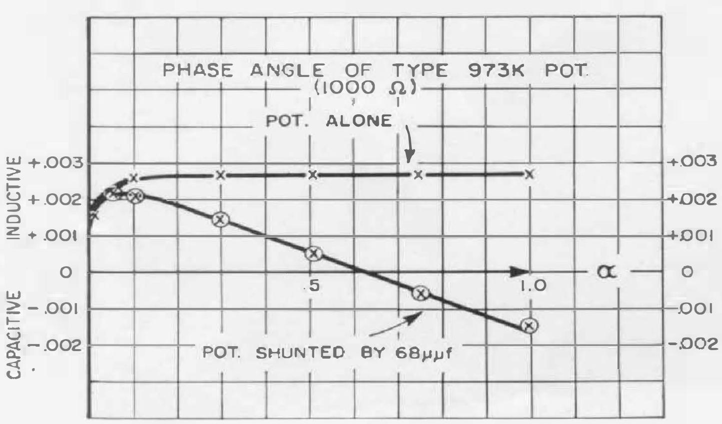


Figure 3.

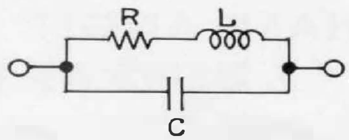


Figure 2.

Figure 4.

Although, in our calculations, the variation in Q is neglected when α is small, this effect should not be overlooked if the phase angle must be accurately known for small angles of rotation. This variation is caused by mutual inductance between the turns of the winding. If the coupling were perfect, the inductance would be proportional to n^2 and α^2, and Q would be proportional to α. However, the coupling extends over only a few neighboring turns, so that, as more and more turns are used, the variation approaches that of the uncoupled case where the inductance increases linearly with n and α.

Rheostat with Lumped Capacitance

If we assume that the stray capacitance is lumped across the terminals as shown in Figure 5, the circuit may be drawn, for convenience in analysis, as shown in Figure 6. The Q for this circuit is:

$$Q = -\omega \alpha R(C_1 + C_2) + \omega^3 \alpha(1-\alpha) R^3 C_2^2 (\alpha C_1 + C_2) + \ldots \qquad (5)$$

The ω^3 term can be shown to be negligible if the first term is less than 0.1. Therefore, we can use the simple equivalent circuit of Figure 7 and the expression

$$Q = -\alpha \omega RC \qquad (6)$$

where $C = C_1 + C_2$, which is a straight line from the origin. When the inductance effect is added to this capacitance effect, the equation becomes

$$Q = \omega(L/R - \alpha RC) \qquad (7)$$

The second curve of Figure 3 shows the inductive pot with added lumped capacitance to illustrate equation (7).

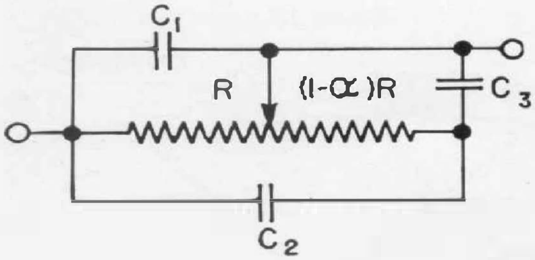


Figure 5.

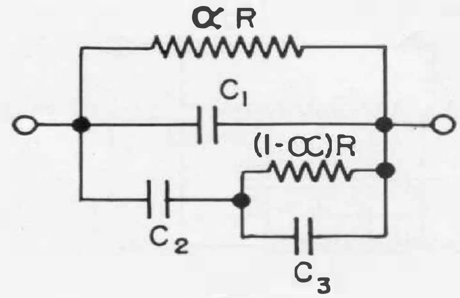


Figure 6.

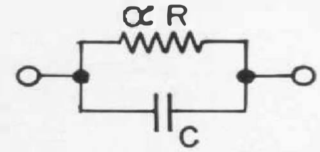


Figure 7.

Equivalent Circuits for Distributed Capacitance

For many rheostats the assumption that the stray capacitance is lumped across the unit is an oversimplification. Better results are obtained if it is also assumed that there is capacitance distributed along the winding to a conductor, which may be the housing, a supporting panel, a metal mandrel, or a shield. The total phase angle can then be calculated as the sum of these fixed and distributed capacitance effects. Because we are concerned with first-order effects only, we can use lumped-parameter equivalent circuits for the distributed circuit of Figure 8. The circuits of Figures 9 and 10 give the same results as the first-order terms of the hyperbolic functions of the well-known transmission-line equations. The circuit of Figure 9 is the more descriptive and uses an interesting division of the capacitance. The second circuit, Figure 10, is simpler to use, however, since it has fewer branches. The effective inductance of this circuit is the result of the capacitance.

An equivalent circuit for a rheostat is given in Figure 11. Here the resistance of the unused part of the winding, $(1-\alpha)R$, is assumed negligible compared to the impedance of the stray capacitance, and the actual inductance of the winding, αL, has been added.

Formulas for Distributed Capacitance Effects

The shape of the Q vs α curve for distributed capacitance effects depends on how the conductor is connected. The conductor could be tied to the rotor, tied to the end of the winding, left floating, or tied to a third terminal. These cases can all be quickly calculated by use of the circuit of Figure 11 and the simple expression of equation (3) above.

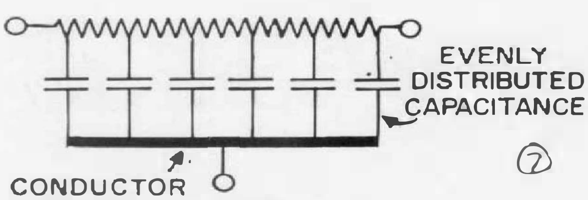


Figure 8.

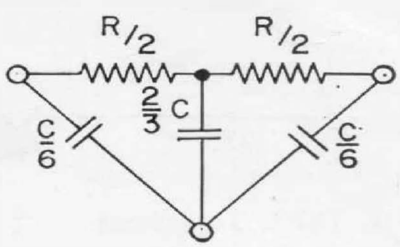


Figure 9.

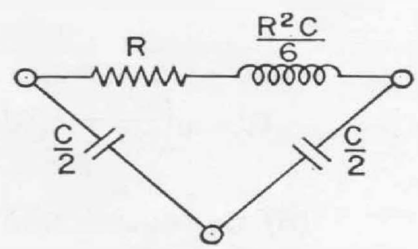
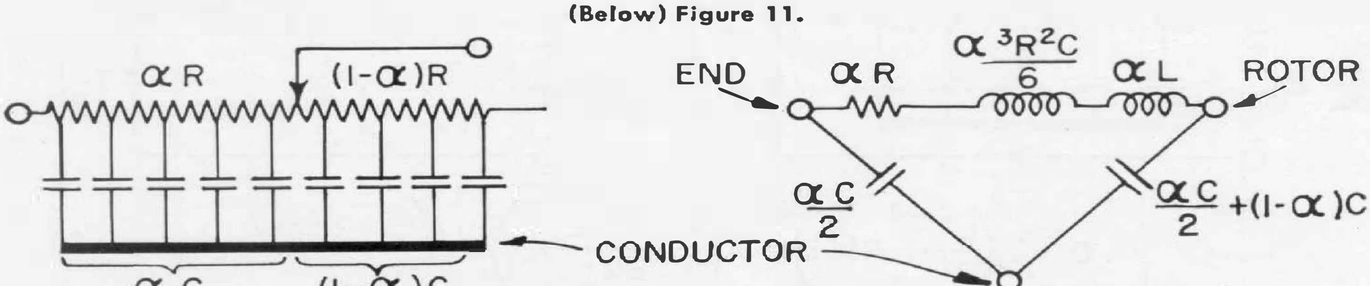


Figure 10.

(Below) Figure 11.



(a) Conductor tied to Rotor (or unused end)

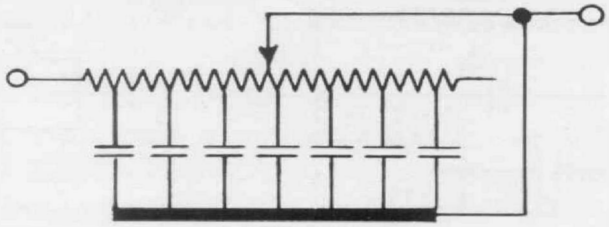
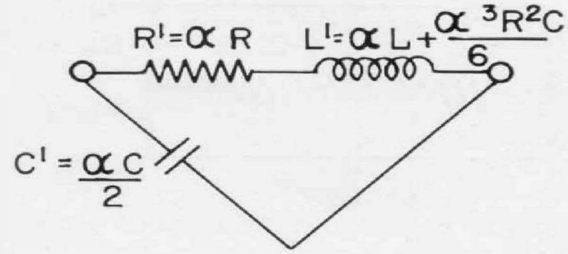


Figure 12.



$$Q = \omega\left(\frac{L^1}{R^1} - R^1C^1\right) = \omega\left(\frac{\alpha L + \frac{\alpha^3 R^2 C}{6}}{\alpha R} - \frac{\alpha R \alpha C}{2}\right) = \omega\left(\frac{L}{R} - \frac{\alpha^2 RC}{3}\right)$$

(b) Conductor tied to End

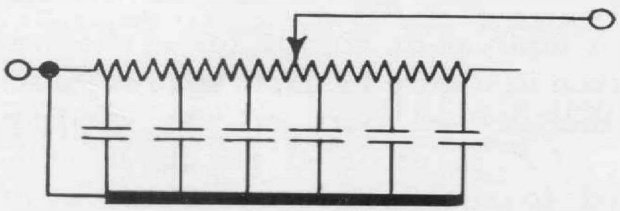
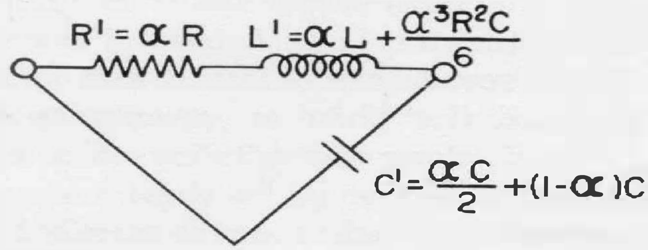


Figure 13.



$$Q = \omega\left(\frac{L^1}{R^1} - R^1C^1\right) = \omega\left(\frac{\alpha L + \frac{\alpha^3 R^2 C}{6}}{\alpha R} - \alpha R\left[\frac{\alpha C}{2} + (1-\alpha)C\right]\right) = \omega\left(\frac{L}{R} - RC\left[\alpha - \frac{2}{3}\alpha^2\right]\right)$$

(c) Conductor Floating

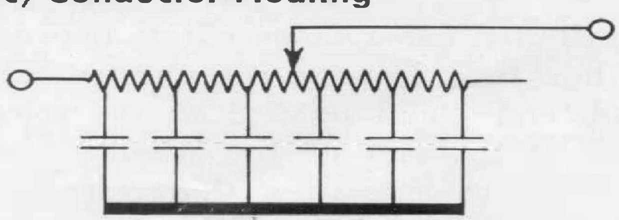
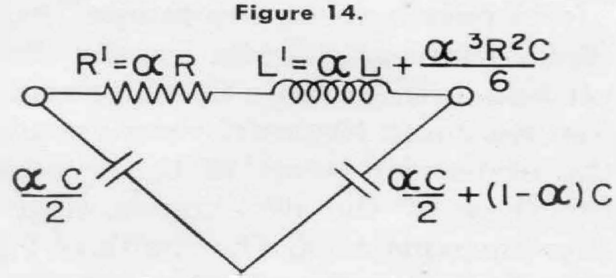


Figure 14.



$$C' = \frac{\frac{\alpha C}{2}\left[\frac{\alpha C}{2} + (1-\alpha)C\right]}{\frac{\alpha C}{2} + \frac{\alpha C}{2} + (1-\alpha)C} = \frac{\alpha C}{2} - \frac{\alpha^2 C}{4}$$

$$Q = \omega\left(\frac{L^1}{R^1} - R^1C^1\right) = \omega\left(\frac{\alpha L + \frac{\alpha^3 R^2 C}{6}}{\alpha R} - \alpha R\left[\frac{\alpha C}{2} - \frac{\alpha^2 C}{4}\right]\right) = \omega\left(\frac{L}{R} - RC\left[\frac{\alpha^2}{3} - \frac{\alpha^3}{4}\right]\right)$$

(d) Conductor tied to a Third Terminal

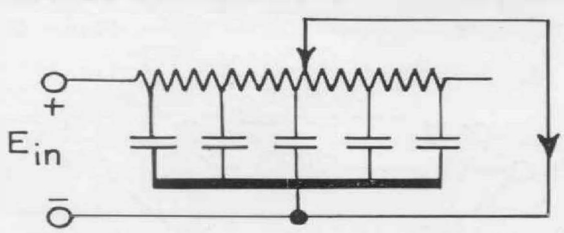
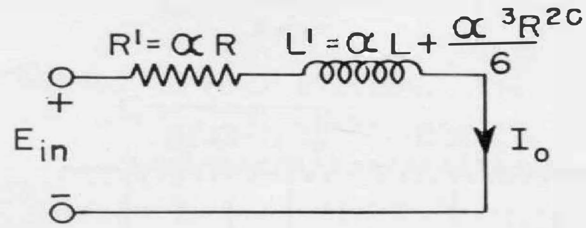


Figure 15.



$$Q = \omega\left(\frac{L^1}{R^1} - R^1C^1\right) = \omega\left(\frac{\alpha L + \frac{\alpha^3 R^2 C}{6}}{\alpha R}\right) = \omega\left(\frac{L}{R} + \frac{\alpha^2 RC}{6}\right)$$

In (d) the Q given is that of the direct impedance, E_{in}/I_e. Note that the capacitive arms of the network of Figure 11 have no effect.

Normalized plots of these functions are given in Figure 16 with the inductance assumed to be zero. Inductance would simply displace the curves upward by $\omega L/R$.

EXPERIMENTAL CHECKS OF CALCULATED CURVES

In order to check these equations, measurements were made on pots that had relatively large distributed capacitance to a conductor, so that the other stray capacitances would be negligible.

Figure 17 shows curves for a pot with a metal shield wrapped around the winding. Note that if the curves are displaced by $\omega L/R$, they are similar to the calculated curves. The small difference could be caused by other capacitances or irregularities in the distributed capacitance.

A good example of the floating conductor case is given in Figure 18, which shows the plot of a ten-turn pot. This unit has a metal mandrel which is left floating. The curve is calculated (the full-scale measurement is used to calculate C) and the measured points are shown.

— H. P. Hall

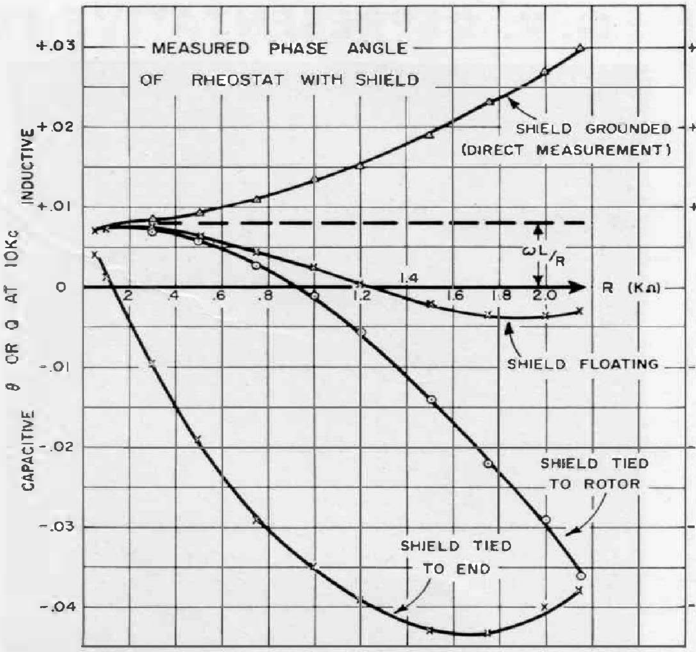


Figure 17.

Results of measurements on a number of standard types of potentiometers will be published in a subsequent issue.

Figure 16.

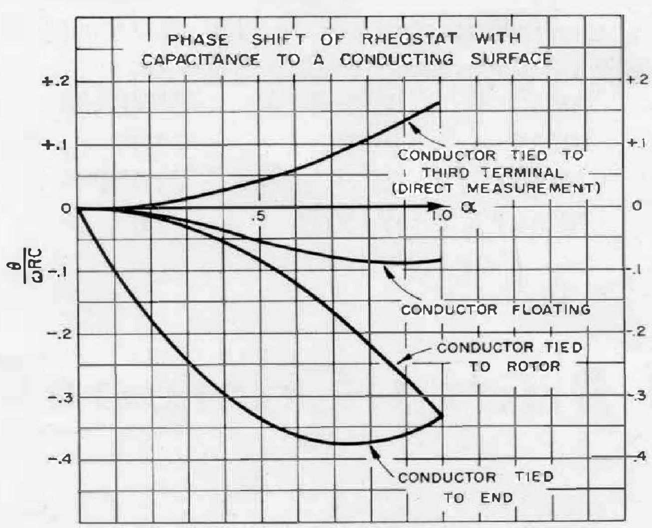
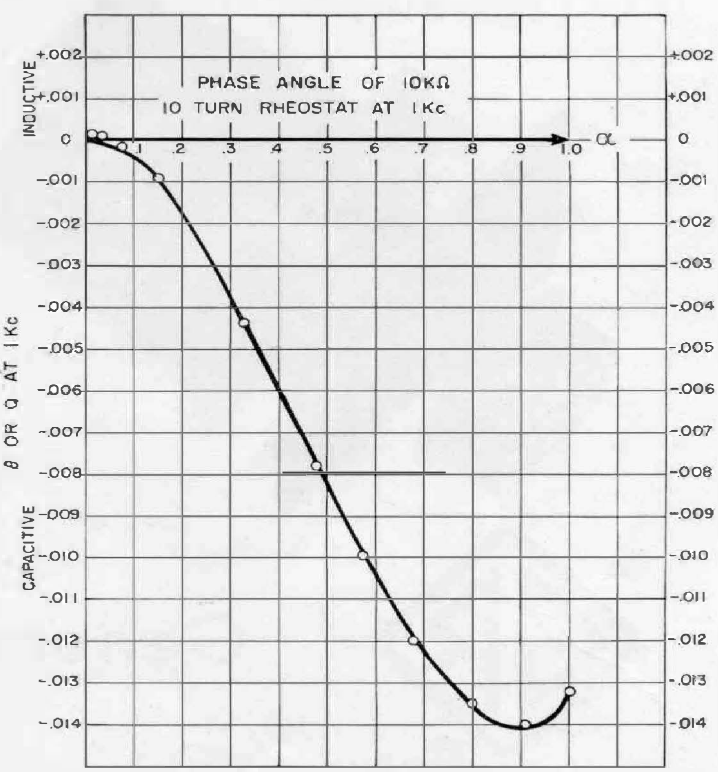


Figure 18.



G. R. REPRESENTATIVE FOR GERMANY APPOINTED

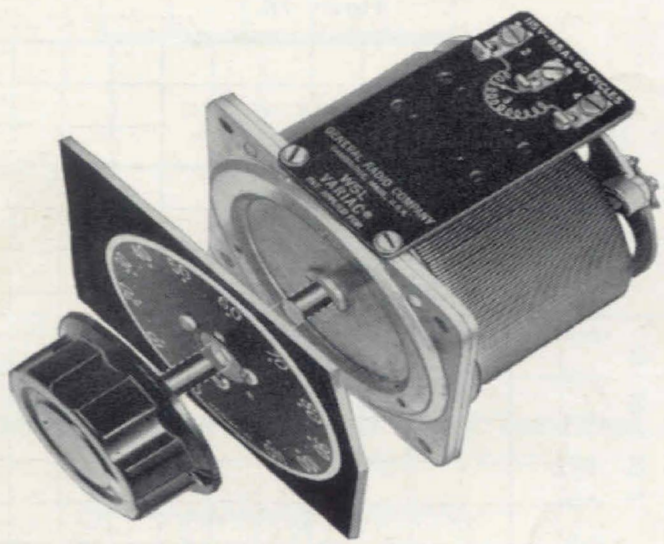
We take pleasure in announcing the appointment of Dr.-Ing. Günter Nüsslein of Ettlingen/Karlsruhe as General Radio representative for Germany.

Complete information on all of our products may be obtained by addressing inquiries to:

Dr.-Ing. Nüsslein
Deutsche Vertretung der
General Radio Company
Ettlingen/Karlsruhe
Dörnigweg 6

Dr.-Ing. Nüsslein is a well-known figure in electronic engineering circles. He received the Diploma Engineer degree in radio engineering and the degree of Doctor of Engineering from the Technical University of Berlin. Since his graduation, he has been associated with prominent research and manufacturing institutions in Germany and for some years was a consulting engineer in private practice. He is the author of many technical articles on electronic matters and has numerous patents and patent applications in the electronics field to his credit.

This appointment was effective July 1, 1957.



UL-APPROVED VARIACS®

We have received word from the Underwriters Laboratories that three additional Variacs are now listed under their Re-examination Service. This brings the number of UL-approved Variacs in the current models to 12. A complete list of approved models follows:

W5	W5MT3	W50HM
W5L	W50	V10
W5M	W50M	V10M
W5MT	W50H	V20

General Radio Company

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