THE MEASUREMENT OF CHOKE COIL INDUCTANCE*

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Summary—*The investigation described has emphasized the facts that:*

(1) The inductance of the choke coil depends upon the degree to which its core is magnetically saturated because of direct current flowing through its winding.

(2) With a given direct current flowing through the winding of a choke coil, the inductance varies to a marked extent with the magnitude of the alternating current flowing through the winding. Methods of measurement which do not take into account or measure the magnitude of the alternating current are, therefore, unreliable.

(3) The inductance for given conditions may be determined from the saturation curve of the coil. It is determined by the average slope of the saturation curve over the range within which the current varies.

Three modifications of the ammeter-voltmeter method of measuring inductance are presented:

(1) The circuit used in the first modification of this method is applicable where only a few approximate measurements are to be made and where simplicity of connection is of the greatest importance.

(2) The second modification of the method involves simplicity of connection and permits of greater accuracy of measurement than does the first modification, but where a large number of measurements are to be made, it involves inconvenience of manipulation.

(3) The third modification of the ammeter-voltmeter method of measuring the inductance of choke coils involves the use of apparatus not always available, but permits of accuracy of measurement and convenience of manipulation.

Introduction

THERE has been a considerable amount of discussion recently concerning the measurement of the inductance of the choke coils used in *B* power circuits. The methods employed by various investigators do not give comparable results. For example, one company manufacturing choke coils proves by measurements that one of its coils has an inductance of 25 henrys while carrying 50 milliamperes of direct current, while another such company reports a value of about 12 henrys for this same coil, carrying the same direct current. Other investigators report other values, differing from the above and from each other.

The present study of the measurement of choke coil inductance has therefore been undertaken in order to develop a reliable method suitable for the comparative rating of such coils. This paper presents three modifications of such a method, together with a series of measurements exemplifying them. The reasons for the variations noted above are also developed.

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THE FUNCTION OF A CHOKE COIL IN A FILTER CIRCUIT

A choke coil consists of a number of insulated turns of wire, wound around and insulated from an iron core. Such a coil may be designed to present a very high impedance to the flow of alternating current, while it provides simultaneously a comparatively low resistance to the flow of a steady direct current. For example, one well-known choke coil under certain typical conditions offers an impedance of over 15000 ohms to the passage of 120-cycle alternating current, and, at the same time, has a direct-current resistance of only 350 ohms.

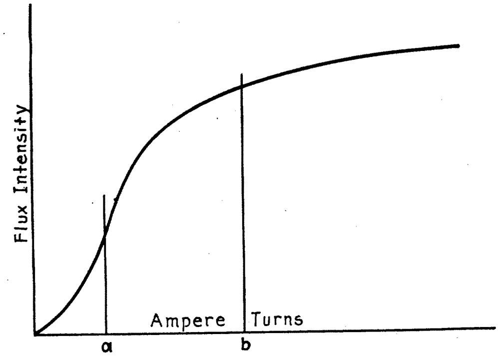

Fig. 1—Typical Magnetization Curve of Transformer Iron.

The choke coil is, therefore, particularly useful in filter circuits in which it is desired to separate the direct current from the alternating current in the pulsating current delivered by a rectifying source. By providing a shunt path of low alternating current and high direct-current impedance (such as the shunt condensers in a filter circuit) the alternating current is induced in large part to take the lower resistance shunt path, while the direct current passes through the choke coils to the load. The higher the inductance of these choke coils, and the higher the capacity of the shunt condensers, the more perfect is this separation of alternating from direct current.

The impedance of a choke coil to alternating current is approximately (the resistance of the coil being neglected) equal to $2\pi fL$, in which f is the alternating current frequency and L is the inductance, which is dependent upon the geometry and character of the iron core and the number of turns and character of the currents flowing in the winding. It is this inductance, L, effective under the current conditions existing in the filter mesh, which determines the filtering or "choking" value of the coil for the given frequency. The determination of L for a given coil, and the influence of various factors on it therefore constitutes the problem of this investigation.

THE SATURATING EFFECT OF DIRECT CURRENT

It is a well-known fact that one of the most important factors affecting the inductance of choke coils is the saturation of the core by the direct current flowing in the winding. Fig. 1 shows a typical saturation curve, in which the magnetizing forces are plotted as abscissas, and the resulting fluxes as ordinates. The magnetizing force for a given coil is directly proportional to the current flowing through the winding, and the resulting flux is dependent upon the number of turns and the nature, size, and shape of the iron core. When the value of magnetizing force (or coil current) exceeds a given amount, the iron core becomes "saturated," and increases in magnetizing force above this point produce but little additional flux. In general, the larger the core and the better its material magnetically, the greater is the direct current which is required to produce this state of saturation.

The inductance of the coil, and therefore, its choking action, is determined by the magnitude of the flux changes produced by the alternating current flowing through it. In other words, *it is determined by the average slope of the saturation curve over the range within which the current varies.* The zero point about which this a-c. variation occurs is determined by the value of direct current which flows through the coil. Thus, if the direct current which fixes the zero point about which the current varies, has a value a in Fig. 1, at the center of the steepest part of the curve, the inductance for moderate values of alternating current will be a maximum. If, however, the direct-current component is of sufficient magnitude to bring the zero point above the knee of the curve (as at b) the inductance is much lower. It is thus apparent that the magnitude of the direct current carried by the coil has a great influence on the effective inductance.

THE EFFECT OF THE MAGNITUDE OF THE ALTERNATING CURRENT ON THE INDUCTANCE

A fact which has been overlooked by many investigators and which is responsible for much of the disagreement among them is that the magnitude of the alternating as well as that of the direct current component affects the inductance of the coil. As the inductance is determined by the average slope of the saturation curve within the limits of a-c. variation, it is apparent that on any but the straight part of the curve, and particularly in the region of the knee of the curve, this average slope is determined largely by the range of the a-c. fluctuation about the zero point. For very low or high values of alternating current, the average slope and consequently the inductance may be lower than it is for intermediate values. It is important in any method of measurement, therefore, that the magnitude of the alternating current as well as the magnitude of the direct current be considered. *In other words, the currents, both alternating and direct, which flow through the coil while it is being measured must be of a magnitude comparable to those which flow through it in the circuit in which it is to be used. Otherwise a false rating is obtained which has no practical application to the problem at hand.* Actual measurements taken on a filter circuit of a typical *B* power supply unit show that the first choke coil carries about five milliamperes of alternating current in addition to the direct current furnished to the load. The combination of 5 milliamperes (RMS) of alternating current and 50 milliamperes of direct current through the choke coil has therefore been chosen in this investigation as a standard in measuring coil inductance for comparative purposes.

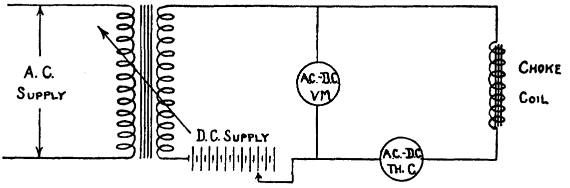

Fig. 2—The Ammeter-Voltmeter Method of Measuring Choke Coil Inductance; First Circuit Modification. (For use where simplicity of connection is important.)

It is in failing to take account of the magnitude of the alternating current that many bridge, ammeter-voltmeter, three-voltmeter, substitution, and fluxmeter methods of inductance measurement are unreliable. In many cases, the value of this a-c. component is not known, and it is frequently very low. In this investigation, however, there have been developed three modifications of the ammeter-voltmeter method which necessitate the measurement of the alternating current, and in which it, as well as the direct current, may be adjusted to any values desired. A discussion of these methods follows.

FIRST MODIFICATION OF THE AMMETER-VOLTMETER METHOD OF MEASUREMENT

The circuit used in the first modification of the ammeter-voltmeter method is shown in Fig. 2. It is applicable where only a few approximate measurements are to be made, and where simplicity of connection is of the greatest importance. Observations are made as follows: With the a-c. source open-circuited at the transformer primary, sufficient B batteries are connected in series with the secondary of the transformer, a thermocouple ammeter, and the coil under test, to produce the desired amplitude of direct current in the coil. The direct voltage required and the direct current are read by means of the a-c., d-c. voltmeter and the thermocouple ammeter. Then sufficient alternating voltage is applied, by means of the variable voltage transformer, to increase the reading of the thermocouple ammeter materially, and the meters are again read.

The inductance calculation is then made in the following manner. When both direct and alternating currents flow simultaneously through an a-c., d-c. ammeter, a deflection is produced which is equal to $\sqrt{I_{ac}^2+I_{dc}^2}$. Similarly, when both alternating and direct voltages are simultaneously applied to an a-c., d-c. voltmeter, the deflection is equal to $\sqrt{E_{ac}^2+E_{dc}^2}$. Having determined, therefore, both the d-c. and the combined deflections, it is possible to solve for E_{ac} and I_{ac}. Knowing that $E_{ac}=(2\pi fL)\times I_{ac}$ the inductance L of the choke coil may be readily obtained by the solution of the equation in which L is now the only unknown quantity. The inductance value so obtained is the value when the measured direct current is flowing through the coil. The resistance of the choke coil is ordinarily neglected in the computation, since it is low in comparison with the reactance and, in addition, is added vectorially to it.

SECOND MODIFICATION OF THE VOLTMETER-AMMETER METHOD OF MEASUREMENT

A disadvantage of the method of Fig. 2 is that in order to obtain differences in current readings sufficient to permit of accuracy in the computed vector differences, comparatively large values of alternating current must be passed through the coils, probably larger than those met with in actual practice. This disadvantage may be avoided by connecting in parallel with the thermocouple ammeter a circuit consisting of a variable resistance, a choke coil, batteries, and a d-c. ammeter, as shown in Fig. 3. If the variable resistance and batteries are so connected in parallel with the thermocouple ammeter that they will send a current through it in the reverse direction, and if the batteries and variable resistance are properly adjusted, all of the direct current may be by-passed around the thermocouple ammeter so that it will not interfere with the measurement of the alternating current passing through the circuit. If the impedance of the choke coil in this shunt circuit is sufficiently large in comparison with the impedance of the thermocouple ammeter, the alternating current will not be by-passed around the thermocouple ammeter by this shunt circuit, and will be read accurately by that meter.

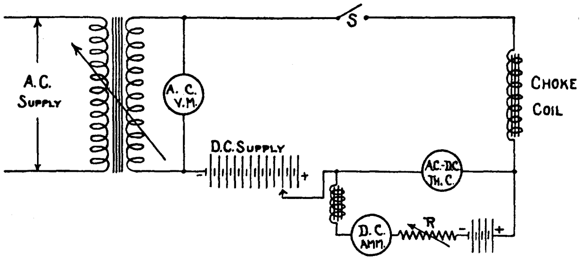

Fig. 3—The Ammeter-Voltmeter Method of Measuring Choke Coil Inductance; Second Circuit Modification. (For use where accuracy rather than simplicity of connection is important.)

If the resistance of the a-c. ammeter is low, an observation is made in the following manner: First, with the a-c. source open circuited, and with the switch *S* also open, the rheostat *R* (in the shunt circuit) is adjusted until the ammeters read the desired value of direct current. Then, still leaving the a-c. circuit open the switch *S* is closed, and the voltage of the d-c. source is adjusted until the reading of the a-c., d-c. ammeter is reduced to zero. The reading of the d-c. meter, however, will be undisturbed, reading the initially chosen direct current which is now being entirely by-passed around the a-c., d-c. instrument.

This latter meter may now be replaced by a more sensitive one, or, if a multi-scale instrument is being used, the switch is thrown to a more sensitive range. The a-c. voltage is now applied and the variable transformer is adjusted to give the desired alternating current through the choke coil. The current is read on the a-c., d-c. ammeter, undisturbed by the direct current component in the circuit. The a-c. voltmeter is connected directly across the a-c. source as shown, where it reads only the a-c. voltage since the d-c. resistance of the transformer winding is so low that no appreciable direct voltage drop is impressed on the meter. Thus, with both alternating voltage and current readings taken separately from the d-c. readings, the accuracy of the method is good.

If, however, the resistance of the a-c., d-c. ammeter is so high as to form an appreciable part of the total resistance in the circuit (as is likely to be the case if a high resistance thermocouple ammeter is employed) it will be necessary to modify the procedure slightly in order to obtain the desired d-c. balance. A short-circuiting switch is provided around the meter, which is closed initially. The resistance *R* is adjusted (with the switch *S*, Fig. 3, open) to give the desired current through the d-c. meter. Then *S* is closed, and the battery voltage is adjusted until a second d-c. meter, connected in the main circuit, reads exactly the same current. The short circuiting switch around the a-c., d-c. or thermocouple ammeter is now opened, and, if the balance is not perfect, both the rheostat *R* and the d-c. source must be simultaneously adjusted. Such procedure is necessary only in extreme cases, however, in which it is desired to hold the direct-current constant at a certain definite magnitude, and where a low value of alternating current necessitates the use of a high resistance am-

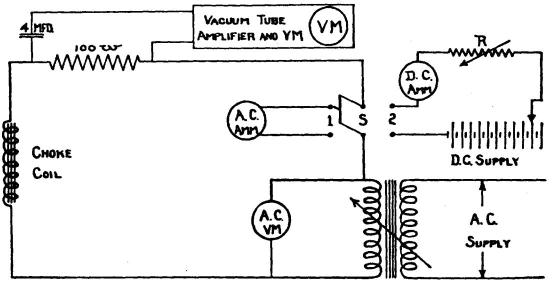

Fig. 4—The Ammeter-Voltmeter Method of Measuring Choke Coil Inductance; Third Circuit Modification. (For use where ease of manipulation and accuracy are important).

meter. Having obtained the d-c. balance, the remaining operations are made exactly as before.

It is apparent that the method of Fig. 3 has the advantages of accuracy and simplicity of connection, but the disadvantage of difficulty of manipulation.

THIRD MODIFICATION OF AMMETER-VOLTMETER METHOD OF INDUCTANCE MEASUREMENT

The method of inductance measurement of Fig. 4 is a special adaptation of the ammeter-voltmeter method which is accurate and which provides convenience of manipulation. It is to be preferred when a sensitive amplifier and vacuum-tube voltmeter are available. Observations are made in the following manner: With the switch *S* in the No. 1 position, the alternating voltage is adjusted to give the desired alternating current through the choke coil as registered on the a-c. ammeter connected across the switch terminals. The d-c. source, connected across the other end of the switch, is not in the circuit and only alternating current flows through the meter and choke coil. A portion of this alternating current flows through the input transformer of the vacuum-tube amplifier, and produces a deflection proportional to the alternating current flowing through the choke coil. From the value of alternating voltage and current so obtained, the inductance of the coil with no direct current flowing through it may be calculated.

The switch *S* is now thrown over to the No. 2 position, removing the delicate a-c. ammeter from the circuit and superimposing the direct current upon the alternating current already flowing in the circuit. The rheostat *R* is now adjusted to give the desired value of direct current, indicated on a D'Arsonval type d-c. ammeter which is not affected by the a-c. component of current which it carries. The alternating voltage is next adjusted to give the same reading on the vacuum-tube amplifier as before, and this new value of alternating voltage, together with the value of alternating current initially chosen, is used to compute the inductance of the coil with the measured direct current flowing through it. In making this calculation, the series resistances in the circuit are ordinarily neglected, since they are low in comparison with the coil reactance, and, in addition, are added vectorially to it.

The reading of the vacuum-tube amplifier is not influenced by the magnitude of the direct current flowing in the circuit and furnishes a convenient method of adjusting the alternating current to the accurately measured initial value flowing when there was no direct current in the circuit. The method lends itself

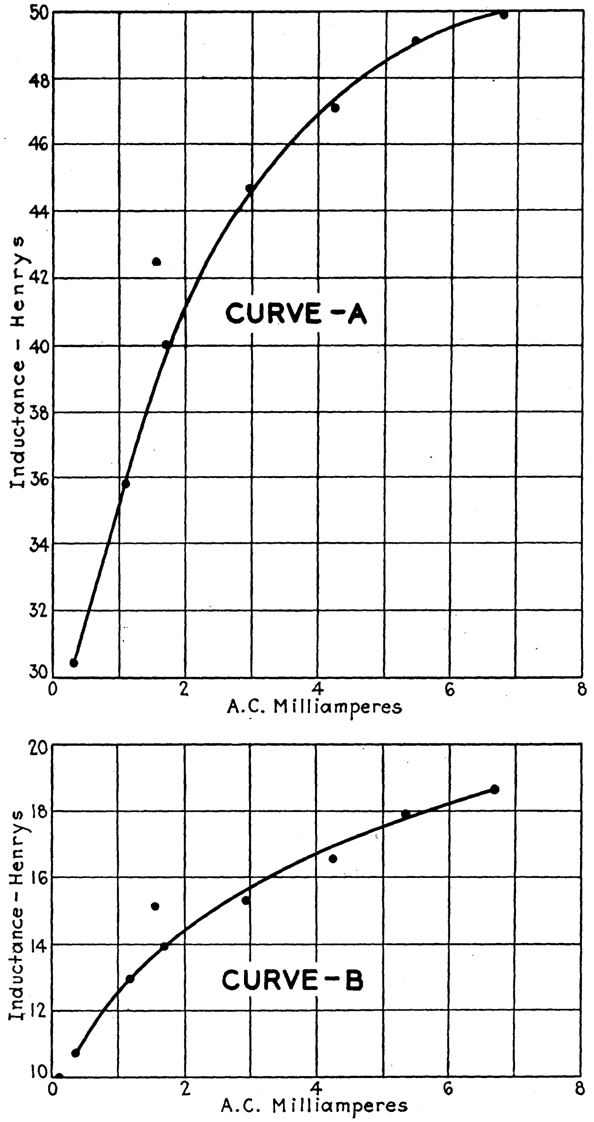

Fig. 5—Variation in Inductance of a Typical "B" Circuit Choke Coil with the Magnitude of Alternating Current.

Frequency 60 cycles. Curve *A*—with no direct current. Curve *B*—with 50 milliamperes of direct current flowing.

readily to manipulation, and permits the adjustment over a wide range of both the a-c. and d-c. components.

INDUCTANCE MEASUREMENTS

In the curves plotted as Figs. 5 and 6, certain characteristic data have been chosen for presentation. Fig. 5 illustrates the variation in inductance of a choke coil with the magnitude of alternating current flowing through it. Curve *A* shows such a curve when no direct current is present, indicating that any inductance rating from 30 to 50 henrys might truthfully be claimed for this coil, provided no mention was made of the alternating-current magnitude. This increase in the inductance with current corresponds to the lower bend in the saturation curve shown in Fig. 1. As the magnitude of the a-c. variation about the zero point is increased, the average slope of the included portion of the saturation curve likewise increases with a corresponding rise in the value of the inductance. Curve *B* illustrates the same variation for the same coil, but with 50 milliamperes of direct current flowing. The inductance values are decreased by the saturating effect of the direct current to almost a third of the values in curve *A*, but the increase with the increase in magnitude of the alternating cur-

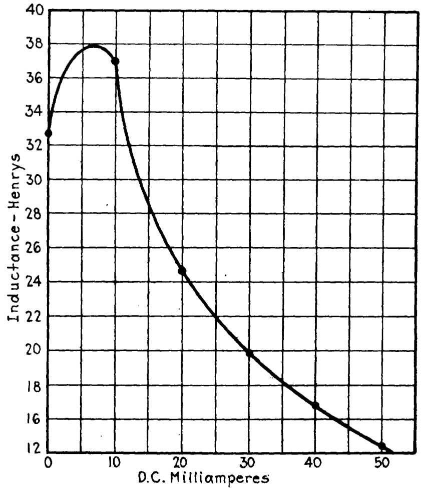

Fig. 6—Variation in Inductance of a Typical "B" Circuit Choke Coil with the Magnitude of Direct Current.
Frequency 60 cycles; 5 milliamperes of alternating current.

rent is still apparent. If the magnitude of the alternating current is not recognized in the measurement of this coil, therefore, values ranging from less than 12 to over 20 henrys might be claimed as its effective inductance in a filter circuit carrying 50 milliamperes of direct current.

Fig. 5 shows the variation in inductance of a typical choke coil with the magnitude of the direct current, the alternating current being held constant at 5 milliamperes. Starting from zero, the inductance rises at first, as the zero line of a-c. fluctuation is advanced to the point of maximum slope of the saturation curve (at *a* on the curve of Fig. 1.) As the direct current is further increased beyong this point which gives a maximum value, the knee of the saturation curve is approached, and the inductance decreases as a result. The effectiveness of this coil in a filter circuit would therefore be a maximum if it carried but 6 or 7 milliamperes of direct current, and it would be less than four-tenths as effective if it carried 50 milliamperes of direct current.

It is because of this saturation at high direct currents that a suitable air gap is included in the magnetic path of a well-designed choke coil. Referring to Fig. 1, a similarly plotted curve for air alone would be a straight line, passing through zero, and rising with increasing ampere turns. The slope of this line is less than that for the iron alone at the point *a* but considerably greater than the slope above the saturation point as at *b*. The combined saturation curve for the iron and air gap together is a proportional addition of the two curves, decreasing the slope of the iron over its steepest range, but materially increasing the slope above the saturation point where the iron is usually "worked" in a *B* filter circuit. The effect of the air gap, therefore, is to increase the inductance of the coil over the range within which it is to be used, even though it does decrease the maximum value obtainable at lower direct-current loads.

Inductance measurements showing the variation in inductance of various types of choke coils with the alternating-current frequency were made. In making these measurements, a substitution method was employed in the following manner. In parallel with the choke coil and ammeter, a variable non-inductive resistance and a second similar ammeter were connected. The output of an audio-frequency oscillator was then connected across the terminals of the two parallel circuits, and the variable resistance in one was adjusted until the currents in both branches were identical. The magnitude of the resistance in ohms is then equal to the impedance, $2\pi fL$, of the choke coil in the parallel circuit, and the inductance L may be readily calculated.

The inductance values obtained at 60 and 120 cycles were in close agreement in all cases. Since 120 cycles is the predominant frequency in double-wave rectification, it is thus permissible to make measurements using the much more convenient 60-cycle source with the assurance that the values so obtained will be a reliable indication of the operation of the coil in a filter circuit. There seems to be a slight tendency for the inductance to rise at the higher frequencies, probably due to the increase in eddy current and hysteresis losses.

Although most of the measurements have been made of the inductance of choke coils to be used in radio B filter circuits, the methods have also been satisfactorily applied to choke coils designed for use in radio A filter circuits.