The Lenkurt® Demodulator

NEWS FROM LENKURT ELECTRIC

VOL. 6, NO. 2

FEBRUARY, 1957

TRANSFORMERS

For Carrier Systems

Transformers are among the most important components of a carrier system. Transmission quality often depends on their performance.

This article discusses the basic theory of transformers and describes the steps in their design and construction for carrier system use.

The electrical form of a telephone conversation begins with a transformer in the transmitting handset and ends with a transformer in the receiving handset. If the connecting circuit is a carrier circuit, many more transformers are at work in between.

In all its applications, a transformer transfers electrical energy. But in doing so, it also performs one or more of three basic functions. It can:

(1) Transform the energy to different values of voltage and current

(2) Change the apparent impedance of the circuit on either side of the transformer

(3) Separate the a-c energy from any d-c energy in the circuit

The design and construction of transformers for carrier centers around the application of basic transformer principles to fulfill one or more of the above functions.

Transformer Theory

Figure 1(a) shows an alternating voltage source connected to a coil. The coil is wound around an iron core and contains N_1 turns. The coil and the core make up an inductance and the current flowing through it sets up an alternating magnetic flux in the core. This flux induces a voltage, E_1, in the coil. The induced voltage is proportional to the number of turns of wire in the coil.

If another coil is wound around the core, as shown in Fig. 1(b), the same magnetic flux will also induce a voltage, E_2, across it. This voltage is proportional to the number of turns of wire in the second coil, N_2. If a load is connected across the second coil, a current

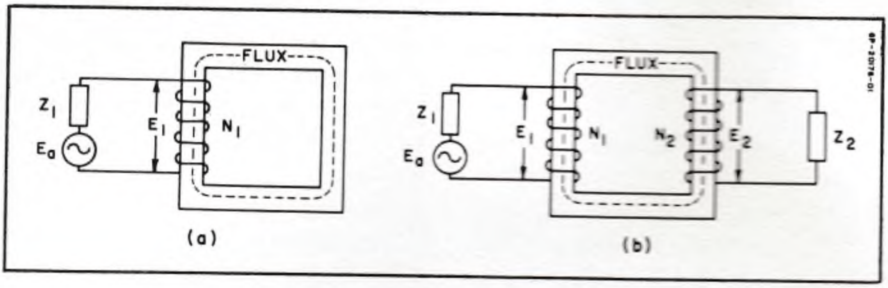

FIG. 1. Diagram showing effect of transformer action. Flux path is shown dotted. Z_1 is the source impedance and Z_2 is the load impedance.

will flow and develop a voltage across the load.

The circuit described is a basic transformer. It has taken energy from a source and transferred it to a load. The coil connected to the source is called the *primary winding* and the coil connected across the load, the *secondary winding*. In practice, a transformer may have several secondary windings to take care of several different loads.

The voltages across both windings are proportional to the rate at which the flux changes in the core. An ideal transformer has no losses and all of the flux links both windings. In such a transformer, the primary and secondary voltages are related only by the number of turns in each winding. Therefore, a given primary voltage can be increased or decreased, as seen from the secondary side, by choosing an appropriate number of turns on each winding. Since an ideal transformer supplies no new energy, nor loses any of the original energy, the primary current, as seen from the secondary side, must change accordingly. And to maintain the voltage-current relationships on both sides of the transformer, the impedance of the primary, as seen from the secondary side, must also change.

Table I gives the voltage, current and impedance relationships of an ideal transformer. In practice, all transformers suffer some power loss in the core and in the resistances of the windings. Moreover, all of the flux does not link both windings. Some of it finds a closed path through the air around each coil and causes leakage reactance. Distributed capacitance also exists between the various conducting surfaces of the transformer. But in most cases, the relationships of Table I are close enough to provide the starting basis for transformer design.

The ratio of N_2 to N_1 is called the *turns ratio*. Table I shows that a primary voltage and current can be changed to a higher voltage and lower current, or to a lower voltage and higher current, by the proper turns ratio.

Table I also shows that the primary and secondary impedances are related by the square of the turns ratio. For example, the impedance of the primary multiplied by the square of the turns ratio gives the impedance that the load circuit sees looking into the secondary winding. This is known as referring the impedance to the secondary side. Of course, the transformer does not actually change either impedance. It simply makes it appear to have a different value when seen from different sides of the transformer.

The "impedance-changing" ability of a transformer makes it possible to match the impedance of one circuit to that of another simply by inserting a transformer with the proper turns ratio between them. This is especially valuable in both voice-frequency and carrier circuits where power reflected by an impedance mismatch can cause undesirable echo or crosstalk.

The flux set up in the core of a transformer changes as the current which causes it changes. Since a steady-state d-c source does not change the flux, such a source induces no voltages in either winding. Therefore, any d-c component of the energy on the primary side of a transformer does not appear on the secondary side. Carrier system transformers often are used for this specific purpose—to separate a-c from d-c. An example of this is the Lenkurt 45BN cable carrier system. In this system, repeaters are remotely powered with d-c which is sent along the same pair of wires as the transmitted signal. An input transformer at the remotely powered repeater separates the a-c from the d-c and passes only the a-c to the amplifying circuits.

Transformer Design

Two of the many problems in designing transformers for carrier are frequency response and size. Often a carrier transformer must pass a wide band of frequencies with a flat response. For example, the Lenkurt 45BN cable carrier system transmits to, and receives from, the line a band 100-kc wide. Size is a problem because the transformer must be small enough to fit in with other miniaturized components of the system and yet large enough to dissipate the heat generated in the core and windings.

As a first step, the transformer designer chooses a core material. Core loss and permeability of the material are the governing factors. Core loss helps to determine how much of the total energy applied to the transformer is wasted. Permeability determines the amount of flux that a given current will set up in the core. The final choice is a material which gives low losses and sufficient flux.

Closely related to the core material is the core shape. The most common form is the shell type shown in Fig. 2. The openings in the core are called windows and the center leg of the core is called the core tongue. The total core is built up by stacking together many thin laminations. This reduces the loss caused by eddy currents which circulate through the core.

For a given frequency and core material, the applied voltage determines

$$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$

$$E_2 I_2 = E_1 I_1$$

$$\frac{I_2}{I_1} = \frac{N_1}{N_2} = \frac{1}{\text{TURNS RATIO}}$$

$$\frac{Z_2}{Z_1} = \left(\frac{N_2}{N_1}\right)^2 = (\text{TURNS RATIO})^2$$

TABLE I. Voltage, current and impedance relationships of an ideal transformer.

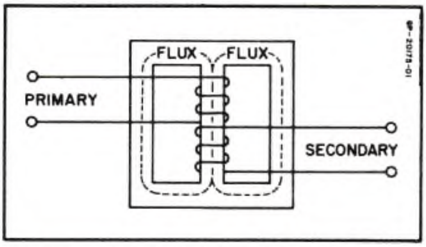

FIG. 2. Shell-type core. Flux path is analagous to current path in a parallel circuit.

the core area. Coil sizes determine the window area. The transformer designer combines calculations of core area and window area to arrive at an over-all size which meets the required dissipation rating of the transformer. The window openings must be large enough to take the number of turns of both primary and secondary windings plus the insulating layers between them.

Figure 3 shows the equivalent circuit for a transformer at low frequencies. Capacitances and leakage reactances contribute only a small effect and are omitted from the circuit. The resistance R_1 is the combined resistances of the source and primary winding and the resistance of the secondary winding as seen from the primary side. This last value is the d-c resistance of the secondary divided by the square of the turns ratio as shown in Table I. In a well-designed transformer, core losses are low and R_2 can be considered as the resistance of the load, referred to the primary side.

The low-frequency response of a transformer is determined by the open-circuit inductance. This is the inductance of the primary with no load connected across the secondary. Open-circuit reactance, X_O, is then the open-circuit inductance multiplied by $2\pi f$.

Open-circuit reactance is shunted across the load. As long as the frequency is high enough to maintain this reactance much greater than the load resistance, the output voltage will remain constant. But as the frequency decreases, the open-circuit reactance drops and current is diverted from the load. The voltage across the load will drop accordingly. Therefore, at frequencies below a limiting frequency, the response of the transformer will fall off. This limiting frequency depends on the open-circuit inductance of the transformer.

The transformer designer calculates the open-circuit reactance that will meet the low-frequency response requirements of the transformer. From this value he determines the open-circuit inductance which the transformer must have. Open-circuit inductance is a function of the number of turns and length of the winding and the cross-sectional area and permeability of the core. High open-circuit inductance is achieved by using many turns of wire or a large core or both.

At high frequencies, the leakage reactances and winding capacitances become important and the open-circuit

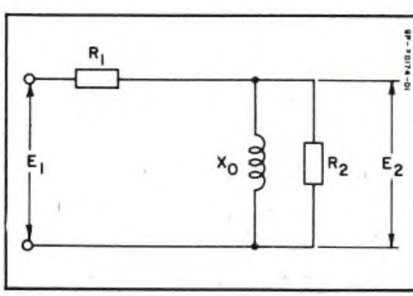

FIG. 3. Equivalent circuit of a transformer at low frequencies.

reactance becomes negligible. Figure 4 shows the approximate equivalent circuit for a transformer which has most of the capacitance on the secondary side. Winding resistances are combined with the source impedance to arrive at R_1 as in the low-frequency case. The load impedance, R_2, is also referred to the primary as in the low-frequency case. The reactance X_L is the primary leakage reactance plus the secondary leakage reactance referred to the primary.

As the frequency increases, the voltage across X_L increases and leaves less voltage available across the load. Also as the frequency increases, capacitive reactance across the load decreases and diverts current from the load. Above some limiting high frequency, the response of the transformer will begin to fall off.

With the high-frequency response requirements known, the designer can calculate the allowable values of leakage inductance and capacitance. He then designs the transformer to meet these values. Leakage inductance depends on the number of turns in the windings and the dimensions of the core, windings and insulation. Capacitance is the sum of several components. These include capacitances between:

(1) One turn and another

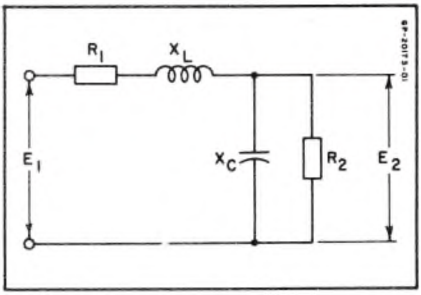

FIG. 4. Approximate equivalent circuit of a transformer at high frequencies. Circuit shown is for transformer having greater number of turns on the secondary. For a transformer having greater number of turns on the primary, X_C is effectively across both X_L and R_2.

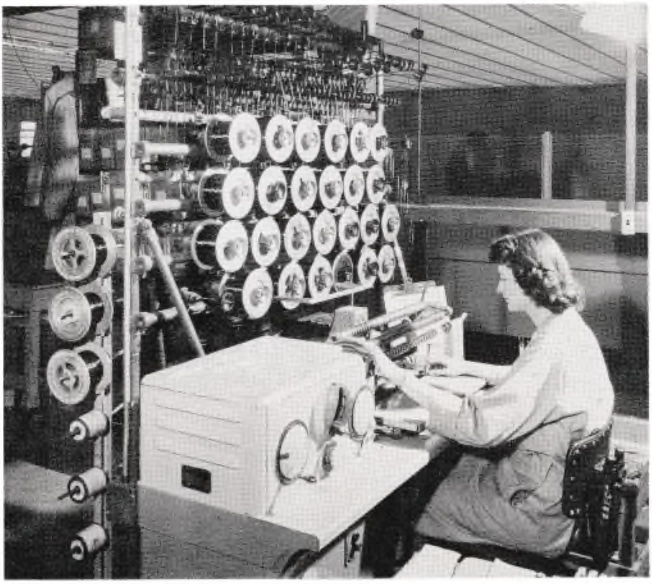

FIG. 5. Transformers being wound at Lenkurt. The machine is winding 20 transformers at one time.

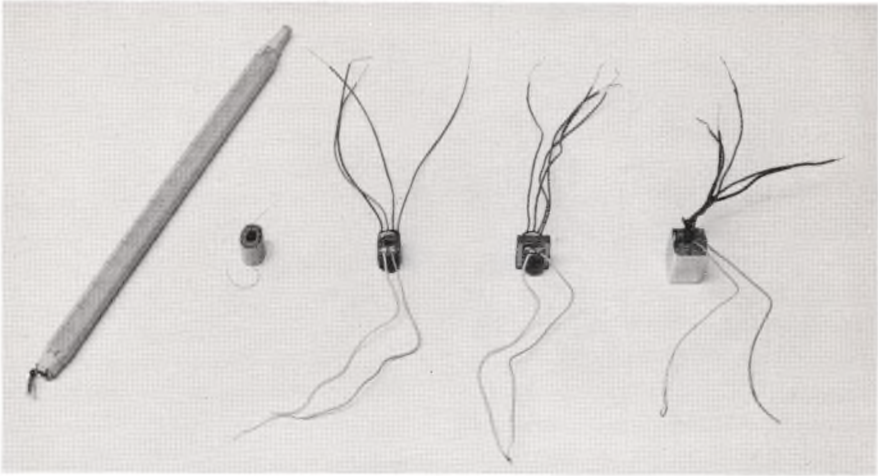

FIG. 6. A miniaturized transformer in various stages of production.

(2) One layer and another
(3) One winding and another
(4) The windings and the core

Stray capacitances of the terminals, leads and case and any external capacitance also contribute.

All of the above design factors are inter-related. Often, a change in one will seriously change the effect of another. Therefore, the first design is usually a trial design which must be modified. Resistances of the windings can be changed by using larger or smaller wire. Capacitance and leakage inductance can be changed by varying the arrangement and shape of the windings.

Transformer Construction

The production of transformers at Lenkurt is devoted exclusively to transformers required for Lenkurt equipment. Construction involves the following basic steps:

(1) Winding coils
(2) Attaching leads
(3) Inserting laminations
(4) Impregnating
(5) Encasing or mounting

For large-scale production, transformers are wound in groups. The number of transformers that may be wound in one group depends on the size of the transformer. Figure 5 shows one of the multi-winding machines at work at Lenkurt. In this case, twenty transformers are being wound at the same time on a common paper core form. As they are wound, the operator places the insulating layers (usually paper) between the layers of each winding and between the windings of each coil.

The long "stick" of windings is sawed to separate and trim the individual transformers. The start and finish ends of each winding are then picked out of the coil and the color-coded leads are attached.

The core is built up of many thin laminations which have been stamped in two sections. When joined together, they form the desired shape of the core. These are inserted in the coil form, lamination by lamination, to build up the required width of the core.

The transformers are then impregnated with varnish. This process takes place under vacuum so that the varnish penetrates into any air space in the transformer. The varnish hardens after drying to form a protective coating which guards the transformer against mechanical damage, moisture and corrosion.

Some transformers may be further protected by encapsulating them in a resin compound. They may also be mounted in cans or fitted with brackets for open mounting. A miniaturized transformer at various stages in its production is shown in Fig. 6.

Modern Methods of

WINDING TOROIDAL COILS

Visitors to Lenkurt factories are often intrigued by the process of manufacturing toroidal inductors used in electric wave filters. At the San Carlos, California plant, more than 5000 are wound each day to a tolerance of 1% or better. Smaller numbers are produced at the Vancouver, B.C. plant. Lenkurt's toroidal coil manufacturing operation is one of the largest and most modern in the world. The machines and methods used to achieve mass production were developed by Lenkurt engineers and production specialists. They are protected by U.S. and foreign patents.

Physically, the toroidal inductor is a length of insulated copper wire wound on a doughnut-shaped core. In use, it is usually interconnected with capacitors to form a resonant or antiresonant circuit in an electric wave filter which selects or rejects specific bands of frequencies. The toroidal shape is not selected because of physical convenience. It is more an electrical necessity. Coils can be wound on any number of different shape cores, but few shapes are as electrically suitable as the toroid. A typical coil is shown in Fig. 1.

Manufacturing

The core material, wire size and type, and winding pattern are determined largely by the electrical characteristics desired. For use in carrier circuits, cores are pressure molded of powdered metal mixed with plastic as a binder. Carbonyl iron or Molybdenum-Permalloy iron powders are the most frequently used core metals. Either stranded or solid wire is used, depending upon electrical requirements.

Once the core has been molded, the manufacture of a coil entails two main operations:

1. Winding the wire on the core
2. Determining the exact amount of wire needed for the inductance desired

The first of these operations is purely mechanical. The second can be achieved roughly by calculation or accurately by measurement. For some applications of toroidal coils, the required amount of wire can be determined by calculating the number of turns to wind. However, an accuracy of only about $\pm 5\%$ can be achieved because of the difference in permeability of individual cores. For filter applications, this is not normally accurate enough. The amount of wire must be determined by measuring the inductance of the completed coil and making adjustments in the number of turns.

The Lenkurt technique combines the operations of winding and inductance measurement and performs them simultaneously. In this way, unit manufacturing time and the possibility of error are reduced.

The Winding Technique

The toroidal coil winding machine winds a coil in much the same manner as if it were wound by hand. In hand winding (Fig. 2) a length of wire is first wound onto a long narrow shuttle that will pass through the hole in the core. The shuttle is then passed repeatedly through the center and around the core until the desired number of turns is reached. As the winding pro-

FIG. 1. Typical toroidal coil.

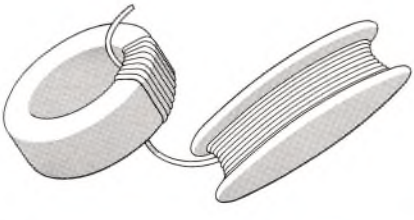

FIG. 2. Hand winding of toroidal coils can be accomplished by the use of a long, narrow shuttle. The shuttle is passed through the center of the coil for each turn.

gresses, wire is unwound from the shuttle.

When used in winding machines, the shuttle assumes a different form—that of a thin, ring-shaped sheave. Various views of the shuttle are shown in Figs. 3, 4 and 5. The inside surface of the shuttle is shaped in such a manner as to allow it to rotate on the machine's three drive wheels. To hold the wire that is to be wound on the core, a groove is machined in the shuttle's outer surface. A cross-sectional view of the shuttle is shown in Fig. 4.

Since the shuttle must rotate through the center of the core, a break in the shuttle (Fig. 4, point A) permits it to be spread apart for insertion in the core. The shuttle and the core are then placed in their respective positions on the winding machine and a supply of wire is wound onto the shuttle.

A *tension pin* (Figs. 3, 4 and 5) slides in small grooves machined on the inside surface of the wire-holding cavity of the shuttle. This pin controls the unwinding of wire from the shuttle. It helps keep the wire uniformly taut during the winding operation. As each turn is placed on a core, a length of wire equal to one wrap around the core is pulled through the tension pin.

FIG. 3. A complete toroidal winding installation. The principal components of the equipment are: (a) turn counter and loading pulleys; (b) inductance measuring panel; (c) standard coil; (d) tension arm; (e) shuttle; (f) oscilloscope; (g) winding machine; (h) core holder; (i) tension pin; and (j) core.

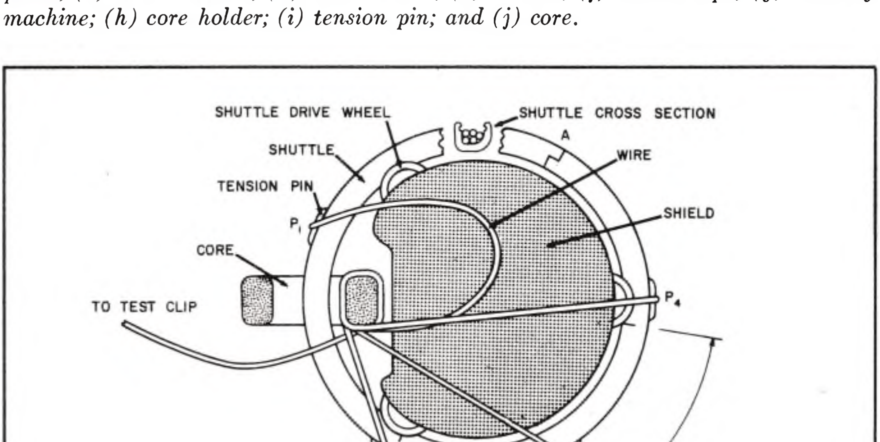

FIG. 4. The shuttle, tension pin, and wire at various stages of the winding cycle. While the shuttle moves through the arc d_1, the tension pin moves through the arc d. The difference between arcs d_1 and d is the length of wire removed from the shuttle and wrapped on the core in one turn.

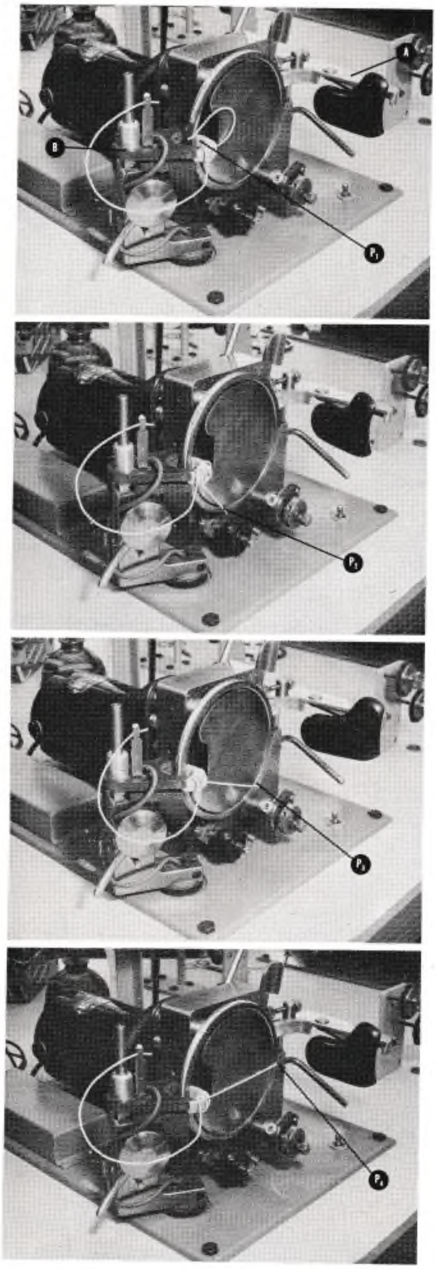

FIG. 5. Four positions of the shuttle during the winding cycle—points P_1 to P_4 in Fig. 4. Ordinarily, fine copper wire is used in the machine; white wire was used in these photographs for clarity.

The process is illustrated by the drawing in Fig. 4 which shows four positions of the wire during the cycle, P_1, P_2, P_3 and P_4. The photos in Fig. 5 show these same four positions on an actual winding machine.

The winding cycle begins at point P_1 where a turn of wire is about to be placed on the core. From this point, the tension pin rotates to position P_2 where the wire draws taut. As the shuttle continues to rotate past P_3, the tension pin slides in its grooves until a length of wire is unwound from the shuttle. At point P_4, the wire ceases to unwind from the shuttle and the tension pin advances again to point P_1 where another turn loop begins for repetition of the cycle.

The *tension arm* (a) shown folded back away from the wire in Fig. 5 normally rides against the loose wire loop and keeps it taut while the shuttle progresses from position P_4 to position P_2. Under operating conditions, the arm is locked firmly into place.

During the winding process, the *core holder* (b) is moved back and forth about a pivot so that layers of wire can be evenly distributed on the core.

Inductance Measurement of Coils

Before the development of present measurement techniques, coils were wound with more turns than calculated to be necessary for an average core. The inductance was then measured and a number of turns were removed to obtain the desired value. Often as many as 100 turns would have to be removed from a core with high permeability to meet requirements.

With use of the measuring technique

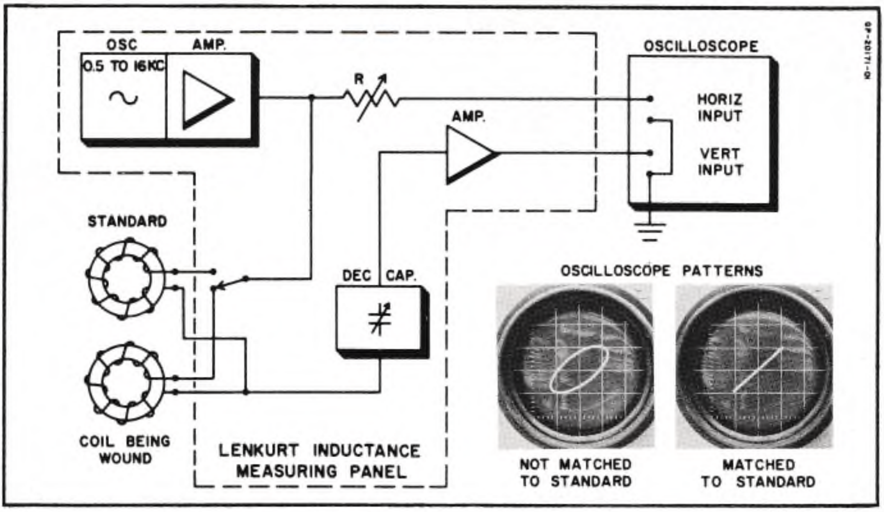

FIG. 6. A block diagram of the inductance measuring equipment. Typical output oscilloscope patterns are shown in the inset.

developed at Lenkurt, the time required to wind and test a coil was cut in half. With this technique, the coil inductance is measured while the coil is being wound. When the desired inductance value is reached, the operator stops the machine and the coil is completed—to a tolerance of 1 per cent or better.

The inductance of the coil being wound is measured by comparing its inductive reactance to that of a known "standard" which is being duplicated. This is accomplished by substituting it during winding for the standard coil in a measuring circuit. To make the comparison, a signal is transmitted through the standard coil and compared to a reference signal by using an oscilloscope. Figure 6 shows a block diagram of the measuring equipment and photographs of typical oscilloscope patterns. A decade capacitor is adjusted so the phase of the signal from the standard coil is identical to that of the reference signal. Under this condition, the oscilloscope screen presents a straight line inclined 45° from the horizontal.

At the beginning of the winding process, the measuring circuit is switched from the standard coil to the unit being wound. The winding is complete when the oscilloscope presentation matches that for the standard. A test clip and a brush which rides on the shuttle during winding constitute the two input leads to the measuring panel.

At the start of winding, the reference and measured signal are out of phase and an elliptical oscilloscope pattern is present. As the coil is wound, the phase difference decreases and the pattern changes into a straight line. At this point, the inductance of the coil being wound equals the inductance of the standard. Once the measuring equipment has been adjusted for a particular coil, additional identical coils can be wound rapidly and measured accurately by observing the oscilloscope pattern.

Lenkurt Electric Co.
San Carlos, Calif.

Sec 34.66, P. L. and R.
U. S. POSTAGE
Paid
San Carlos, Calif.
Permit No. 37

W. F. CRUESS, DESIGN ENGR.
WESTINGHOUSE ELECTRIC CORP.
SWITCHBOARD ENGINEERING DEPT.
EAST PITTSBURGH, PA.

Form 3547 REQUESTED 20

A Recently Issued Publication

The engineering of **Lenkurt Type 72 microwave radio systems** is discussed in detail in a new 56-page bulletin, **72-ENG.** Sections are included on comparative costs, licensing, equipment characteristics, antennas, transmission path characteristics, and system layout.

Type 72 microwave radio systems operate in the 890-960 megacycle range. Three complete radio circuits can be transmitted over a single path. Each radio circuit can be channelized with as many as 120 telephone channels to obtain an effective route capacity of 360 channels.

The **72-ENG** is available on request from Lenkurt plants or distributors.

LENKURT ELECTRIC

SAN CARLOS, CALIF. • VANCOUVER, B.C. • MEXICO, D.F.

Automatic Electric Company and Automatic Electric International Inc., Chicago, and their affiliates are distributors of Lenkurt products.

The Lenkurt DEMODULATOR is a monthly publication circulated to individuals interested in multi-channel carrier, microwave radio communication systems and allied electronic products. Permission to reproduce material will be granted upon request.

Litho in U.S.A.