which a lo[illegible] back at some old devices provides insight into some useful new concepts.

Electromagnetics Made Interesting or Cores Need Not Bore

BY IRVING M. GOTTLIEB,* W6HDM

A sure-fire way to turn off a ham's intellectual appetite is to serve him an entree of *electromagnetics* prepared in the ordinary way. Who, after all, wants to regurgitate the hors d'oeuvres gobbled down (and hopefully digested) so much earlier on the menu? At the outset, the yearning for soul food a la technicania was kindled by transformers, reactors, solenoids, and morsels of kindred kind. But now, the satiated patron needs a change in cuisine. A chef's good reputation stems in large part from his ability to evoke culinary miracles—he must deliver tasty tid-bits from blaze raw-material, such as even the egg plant! And, it is respectfully submitted that an author worthy of his salt, should likewise cultivate the skill of transforming the ordinary into the desirable. (Such as even the hum-drum and excessively-recycled theme of electromagnetics.) As the chef has graciously informed us, the clue to such an accomplishment is to prepare it in an extraordinary way.

So, rather than rehash the conventional stuff found in any good technical cook book, the endeavor will be to whet the appetite with a few devices, concepts, and behaviourisms which have not been easy to swallow, or which have been tempting, but not taken because of controversial reports from previous partakers. It may well be that some long overdue clarifications will emerge. In any event, our discussions should lead to some profitable transactions — wherein some wrong answers can be horsetraded for some right questions.

A well-known electromagnetic function block is the d.c. to a.c. inverter shown in fig. 1. In the technical literature, one finds that this circuitry is also referred to as a saturable-core oscillator, and as a magnetic multivibrator. The predecessor of the modern solid-state inverter was the erstwhile vibrator power-supply, which provided the requisite translation of dc voltage level for auto radios. A typical vibrator supply is shown in fig. 2a. The vibrator was, in essence, a doorbell buzzer designed to enhance current chopping, but to de-emphasize sound production. A contact-carrying armature was set in vibration by the competitive

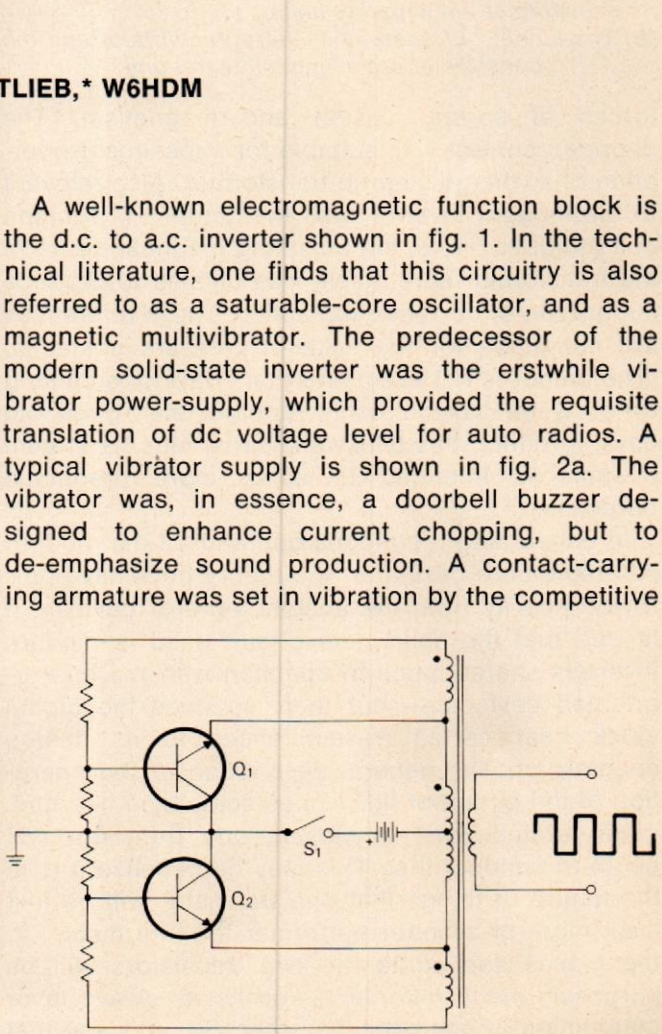

Fig. 1—THE d.c. TO a.c. INVERTER—AN ELECTROMAGNETIC ENIGMA

Most descriptions of the operating theory tell us why oscillation commences when Switch Sw-1 is closed. But suppose the circuit is in operation, and a short is placed across the output winding, then removed—why should this restore the circuit to its oscillatory condition?

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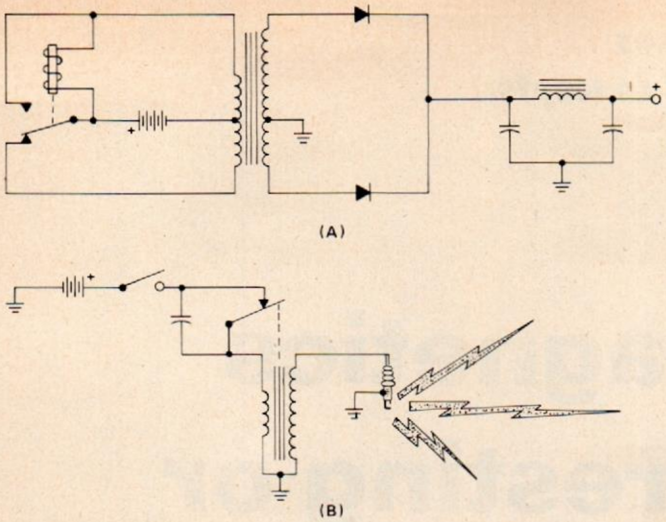

Fig. 2—STONE-AGE PROGENITORS OF THE SOLID STATE d.c. TO a.c. INVERTER

(a) The vibrator power supply sometimes used selenium rectifiers, but more often employed a cold-cathode tube. In this scheme, the vibrator and the step-up transformer are separate units.

(b) The Model "T" spark coil—here the vibrator and the transformer are a single integral unit.

forces of spring tension and magnetism. The chopped current was suitable for subsequent operation of a voltage step-up transformer. Also relevant to the modern inverter, was the Model "T" ignition coil of fig. 2b. Here, the pulsating magnetic force in the transformer core, itself, was utilized to produce the buzzer, or current-chop action. These references are not made for the sake of pleasant nostalgia. (The author is not even sure that "days of auld lang syne" were, as commonly reputed, the "good old days.") Rather, this backward thrust into the stream of time is intended to serve more pragmatic purposes.

In concocting the modus operandi of the modern saturable-core oscillator, the theory boys have borrowed heavily from the ancient vibrator devices. It is true that the solid-state circuit used in modern inverters shares much in common with the buzzer-oriented devices — but then, so does the digital clock bear certain resemblences to its analog counterpart. The general description of the operation of the circuit of fig. 1 goes something like this: When switch Sw-1 is closed, one transistor will begin to conduct first. This may be because it is in the nature of things that one transistor will be just a bit more of a hotter performer than its mate. Or, the biases applied to the two transistors will be purposely made different — so as to always favor conduction in one over the other. So, let's say that the pecking order is skewed in favor of Q1; it always beats Q2 to the current when switch Sw-1 is closed. As the emitter-collector circuit of Q1 begins to consume current through its half of the transformer winding, current is induced in its feedback winding, and in such a direction that the base of Q1 is driven deeper into its forward-conduction region. The effect is regenerative and proceeds vigorously. We might suppose that the closure of the switch started things going from a point such as "X" on the core hysteresis loop illustrated in fig. 3. And, if all goes well, we can anticipate landing at point "A" very soon.

It should be borne in mind that, not only is Q1 indulging in a regenerative turn-on, but Q2 is being progressively driven further into its cut-off region. This action is brought about by the current induced in the feedback winding associated with Q2. A study of the phasing dots pertaining to the transformer windings of fig. 1 will reveal that a given direction of current in the center-tapped winding will always reinforce conduction in one transistor, and simultaneously cut the other one off. Inasmuch as we suspected that the transistors *alternate* their conductive states, so far, so good.

When point A on the hysteresis curve is closely approached, the rate of increase of flux density in the core abruptly slows down, this being accompanied by a drastic reduction in the magnitude of currents induced in the feedback windings. If we suppose that Q1 was driven into collector current saturation by the time point "A" was reached, it now begins to come out of saturation (for lack of strong base drive). This enables the tracing of path "A" to "B" on the hysteresis curve. In the vicinity of point "B" the changing core flux reverses th polarity of the feedback circuits and we sudden find Q2 being driven into conduction and Q1 being turned off. Again, the process is regenerative and

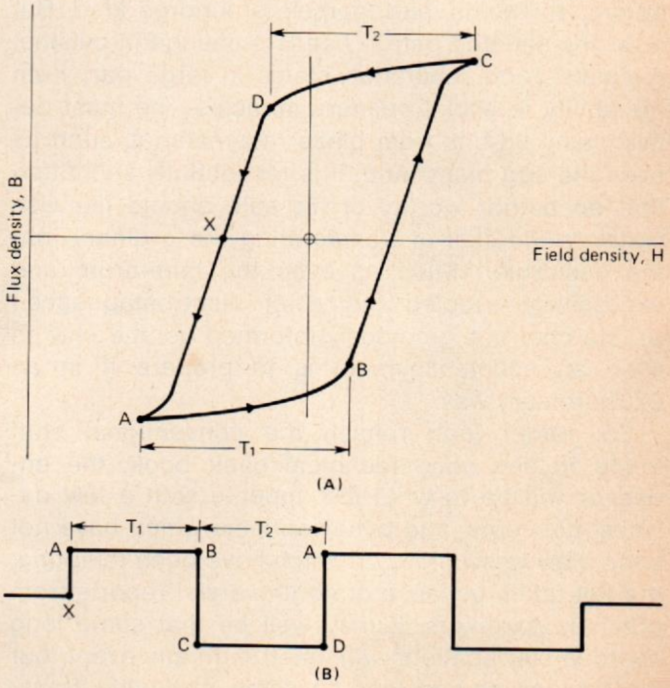

Fig. 3—HYSTERESIS LOOP OF CORE AND THE OUTPUT VOLTAGE WAVE OF THE d.c.-a.c. INVERTER
The roll played by magnetic hysteresis in the operation of the inverter is generally not clearly delineated.

we wind up at point "C". The journey from point "C" to point "D" is analagous to that described between "A" and "B". So, to make a long story short, the process is repetitive, *once started.* For practical purposes, the transistors are caused to behave as knife switches and a rectangular voltage wave results.

The foregoing theory of operation is skeletal — there is much room for detailed mathematical analysis. Admittedly, such analysis can readily be shown to be valid, for we can establish the relationships between such engineering parameters as the applied voltage, oscillation frequency, and core characteristics. Not only is this fine and dandy, it is essential, for otherwise we would tend to avoid the phenomenon as an interesting, but unpredictable occurrence. But, the author has found something missing in even the most detailed treatment of this electromagnetic device. Suppose that the inverter of fig. 1 *was* in operation and the output winding was short-circuited. It is a tribute to the compliant nature of this circuit that such a short need not be destructive at all. In well-designed inverters, oscillation simply ceases and the transistors are returned to their quiescent states of conduction (because one transistor is generaly slightly forward-biased in order to promote starting, that transistor will draw a moderate current when oscillation is inhibited).

Not only can such a short be safely endured for many minutes, or even hours, but normal operation immediately ensues when the short is removed! *Why?* The removal of the short from the output winding cannot be construed to be the equivalent of closing the battery switch, Sw-1. The latter event produces a *transient current* in the center-tapped winding, and this current is regeneratively acted upon by the "turned-on" transistor. But, *lifting the short circuit* cannot produce such a transient current in the center-tapped winding. And it would be quite far-fetched to assume that a winding associated with an active device must necessarily develop cyclical currents under the "guidance" of a core's hystersis loop. We can clearly see why the vibrator supply, or the Model "T" ignition coil can come alive after removal of an output short, but the starting mechanism in the solid-state inverter under similar conditions is more elusive.

It is all too easy to think of the inverter as a *magnetic multivibrator,* that is, as the inductive counterpart of the RC multivibrator. Such circuits do indeed exist and assume the general configuration shown in fig. 4. (Simple inductors, rather than transformers may also be used, but it is then necessary to involve capacitors in the base circuit. To keep the idea being pursued simple, the transformer circuit of fig. 4 will best suit our needs.) The frequency of this relaxation oscillator is a function of L/R in an analagous way to which the frequency of a conventional RC multivibrator is governed by the RC time-constant. *If* this circuit simulated our inverter, it would be found that the L/R influence on repetition rate would prevail. This is decidedly *not* the case. The oscillation transformer or fig. 1 can, in principle, be wound with a wide range of wire sizes with little effect on frequency. (What effect there is, may be shown to be related to the ohmic drop of voltage applied to the transistors, and not to an L/R time constant.) Clearly, our inverter is *not* such a magnetic multivibrator, technical literature notwithstanding!

We may, of course, have allowed ourselves to become ensnared in a gray area of semantics. Perhaps

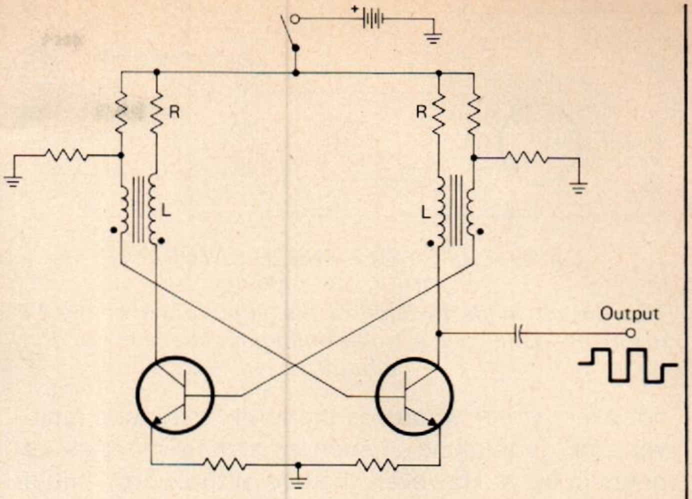

Fig. 4—A TRUE MAGNETIC MULTIVIBRATOR
In this circuit, oscillation frequency is governed by the L/R time constants of the two non-saturating *transformers. "R" can either by physically discrete resistances, or can be the inherent resistance of the collector windings themselves. This circuit is the inductive counterpart of the common RC multivibrator. The operational mode is decidedly* different *from that prevailing in the d.c. to a.c. inverter of fig. 1.*

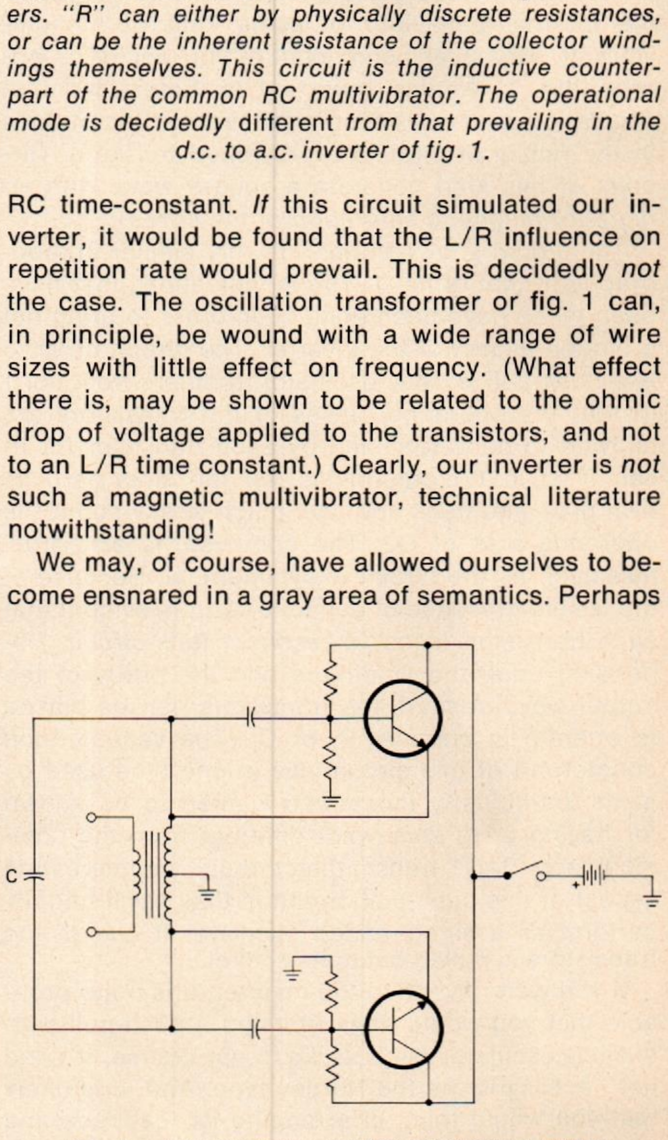

Fig. 5—A PUSH-PULL HARTLEY OSCILLATOR
This circuit resembles that of the d.c.-a.c. inverter of fig. 1. However, a "visible" tank-circuit is provided, and oscillation does not *depend upon saturation of the core, if one is used. Also, the bias circuits are such that one transistor does not turn the other one off during the oscillation cycle.*

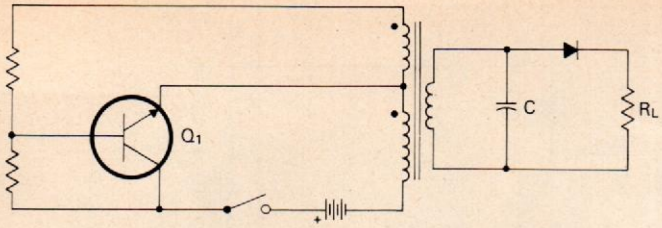

Fig. 6—THE SINGLE-ENDED SATURABLE CORE OSCILLATOR
This circuit tends to confirm the importance of the LC resonant "tank" as a contributing mechanism to core saturation.

not every writer who uses the term "magnetic multivibrator" is thinking of such an arrangement as appears in fig. 4. However, the use of the word, "multivibrator" does tend to conjure up notions of an L/R relaxation oscillator. It might even be argued that the overall performance of the inverter suggests the internal behaviour of some kind of a multivibrator. Whatever nomenclature you decide is appropriate, it remains important to understand that oscillation does *not* occur in the manner that it does in the family of circuits represented by fig. 4. Circuits of this kind generate a square wave with *no need for magnetic saturation* of the cores.

The circuit shown in fig. 5 is very similar in topography to that of fig. 1. The modifications that have been made have been done so in order to bring out a hidden aspect of the inverter. The circuit of fig. 5 is a push-pull Hartley oscillator. It differs from fig. 1 in that the operating biases of the transistors are allowed to be determined by each transistor for itself. That is, Q1 determines (for the most part) its own bias, and does not have much to say about the operating bias of Q2. The converse, is also true, inasmuch as the circuit is symmetrical. Because of the visible presence of capacitor C, it is evident that each transistor "sees" a *resonant tank-circuit.* Depending upon the amplitude and the purity of the output wave desired, the transistors can be biased to operate in class A, B, or C. (The vacuum-tube counterpart of this circuit was at one time used by hams, particularly those who wanted to be known for having a rig somewhat different from the commonplace "TNT" transmitting circuit.) An interesting aspect of this push-pull circuit is that it will happily perform as a single-ended oscillator if *one* of the transistors is pulled out of its socket.

If you were inventing the inverter, it is quite probable that you would think of using a push-pull self-excited oscillator such as fig. 5. Of course, it need not necessarily be the Hartley type. And, it is likely that you would think of arranging its feedback and its "grid-leak" bias so as to attain an over-driven condition. In this way, you would get a non-sinusoidal output — maybe a trapazoidal wave. But, you would never coax a nice square wave out of it. In the course of your experimentation, it is conceivable you might stumble upon the unique operational mode of the inverter. Supposing that such serendipity prevailed, it would be well to remember how you got to the final result, for the cyclic generation of the hysteresis loop in no way obscures the fact that the basic configuration of the circuit remains that of a push-pull Hartley oscillator. This remains so even though the frequency of the new mode of operation is not determined at all by the resonant tank-circuit — it is assumed that a tank exists in the inverter of fig. 1 by virtue of the distributed capacitance in the windings.

Having now covered topics which may appear divergent, or of questionable relevance to our probe into the operating theory of the saturable-core oscillator, it is probably timely to tie things together. What has been inferred, and what is now stated in so many words is that one of the ways in which this circuit can *start* is by attempting to oscillate as an LC oscillator. This attempt quickly gets the core into saturation, whereupon other mechanisms assert themselves and maintain operation in which the hysteresis loop of the core is repetitively traced. The resonant frequency of the LC tank is very high. This is generally true because the tuning capacitance derives mainly from *stray capacitance* in the windings themselves. However, the resonant frequency is still much higher than the switching rate of the transistors even when a physical capacitor is connected across the "tank". Such a capacitor appears in many circuits as a means of attenuating switching spikes. Because of the tendency of the LC oscillation to be high in frequency, the switching transitions can be very fast — as the 'scope display of the output wave from these circuits reveals.

Thus, when the secondary short is removed, the circuit will commence an LC oscillation. It is true that the "tank" Q presented may be quite low, because of the low C/L ratio for parallel resonance. But, at the same time, it is to be remembered that power transistors have exceedingly-high transconductances. The mere *start* of an LC oscillation suffices to speedily bring the core to point "A" in on the hysteresis loop of fig. 3. Thereafter, the oscillation mode is governed by the hysteresis loop in accordance with the explanation previously given.

Suggestive evidence that such reasoning is valid is provided by the circuit of fig. 6. Here, we have essentially a single-ended version of fig. 1. Operation is similar, but efficiency is lower, and the action is not so sure-fire. This circuit often appears in d.c. supplies for Geiger tubes, or for other low-power loads. The capacitor, C, is generally given credit for "resetting" the core in lieu of an alternate switching transistor. From our point of view, however, this is a *resonating* capacitor for the "tank". Such a physical capacitor provides the LC circuit with a higher Q, that is, with greater energy storage than would obtain from stray-capacitance alone.

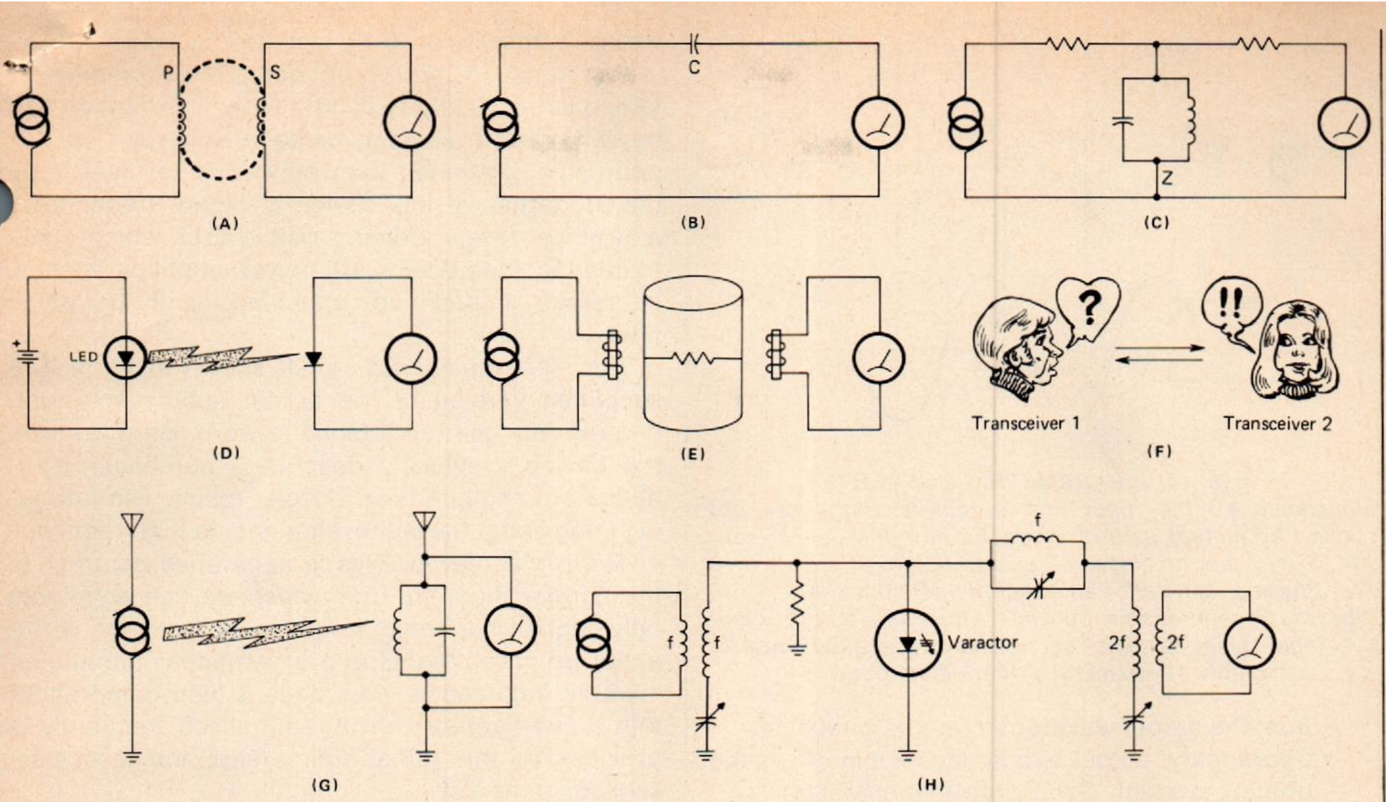

Fig. 7—A FEW OF THE WAYS IN WHICH ELECTRICAL ENERGY CAN BE TRANSFERRED

(A) Transformer action—input and output windings are linked by mutual magnetic flux.
(B) Capacitor "displacement" current.
(C) Common circuit impedance, Z.
(D) Opto-coupler
(E) Nuclear magnetic-resonance. (Exciting coil and pick-up coil are arranged at right—angles to one another to prevent ordinary transformer-coupling.)
(F) Extra Sensory Perception. Often alleged to be instantaneous and independent of distance.
(G) Radiation at radio frequencies
(H) Parametric frequency doubler.

Interestingly, this circuit also takes the form of a free-running blocking oscillator. Virtually all literature dealing with the principle of operation of the blocking oscillator associate the *rise* and *fall* of the pulses to the constants of the LC "tank".

Hopefully, we are now convinced that a hysteresis loop does not, of its own intrinsic nature, supply negative-resistance, amplify, or produce dynamic switching. We may next investigate a very interesting mode of electrical energy transfer based on a novel electromagnetic-device. How many ways can you think of for transferring electrical energy? There are, of course, electromagnetic coupling (transformer action), capacitive coupling via the so-called "displacement current", couplings brought about by mutual impedance between circuits, and electromagnetic radiation. A few of these energy transfer mechanisms are illustrated in fig. 7.

There is, however, yet *another* arrangement for coupling electrical-energy from one circuit to another; one that has been somewhat overlooked theoretically, and neglected in practice. Consider the crazy device shown in fig. 8a. A goofy transformer if ever there was one! But, hold on a moment —*this is not a transformer,* for the magnetic flux of the "primary" winding certainly does not link the turns which comprise the output, or "secondary" winding. Every transformer is, first, and foremost, dependent upon a magnetic flux which is *mutual* to both windings. What goes on here?

For want of a better name, we may call the contraption of fig. 8a a *parametric converter.* The inductance of the output circuit is *modulated* by the magnetic flux of the input circuit. This occurs because of the generally non-linear relationship that exists between the magnetic permeability of ferromagnetic material and the magnetizing force. It happens to be a fact of life that energy can be "pumped" into a circuit if its inductance is varied. But, the "pumping" must occur in such a way that more energy is transferred into, than out of, the circuit by the pumping action. This requirement is satisfied when the input frequency coincides with the resonant frequency of the output winding. Under such conditions, the phase conditions shown in fig. 8b prevail. Note that, unlike the conventional transformer, where the induced secondary voltage is either in phase, or 180 degrees out of phase with the primary voltage, this phase relationship is *ninety degrees* for the parametric converter. Other interesting features of this device are as follows:

- Off-resonance, the output falls to zero. (Except that it will also operate as a frequency multiplier when the source supplies a sub-multiple of the resonant frequency.)
- No matter what the wave shape of the excita-

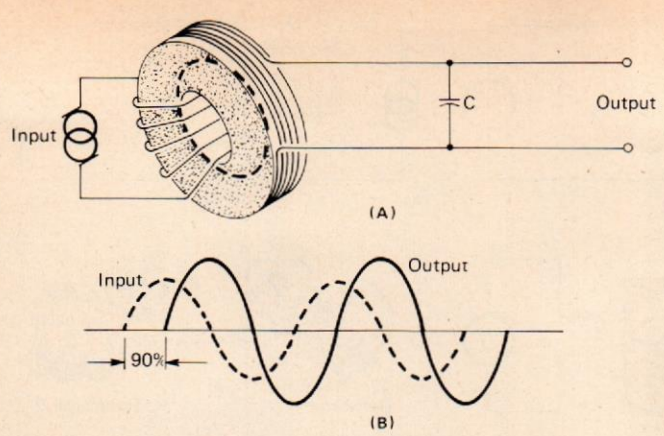

Fig. 8—THE PARAMETRIC CONVERTER
Inasmuch as the input and output windings are not linked by mutual path of magnetic flux, the device cannot be classified as a transformer.
(a) Physical details for an experimental converter.
(b) Phase relationship between input and output windings. This pertains to resonant operation. Appreciably off-resonance, there is no output.

tion, the output waveform remains *sinusoidal.*

- *Shorting* the output circuit does not increase the primary current. Oscillation then ceases.
- The device is not bi-lateral; if the excitation is applied to the output winding, no energy is transfered to the input winding.
- As a corrolary of the above described behavior, the device provides very high rejection of transients produced by either source or load.

The author made the experimental parametric converter of fig. 7 by placing the two windings on a 2″ OD powdered-iron core of the type commonly used for antenna baluns, r.f. tanks, etc. These have cross sectional area of ½″, and are convenient to work with. Approximately fifty turns of #26 enamel wire used on both the input and output windings. The toroidal (input) winding should be placed on the core first, and it can occupy sixty to ninety degrees of the core circumference. Both windings can be either layer, or "scramble" wound. With an output capacitor of 0.05 μF, operation should be attained in the 40 kHz to 60 kHz region. Excitation can be with sine, triangular, or square waves. The experimentally-inclined ham may wish to investigate the properties of this device at higher frequencie and power levels. Some possible uses which come to mind include baluns, RF power amplifier "tank"s, interstage impedance matching, and harmonic filters.

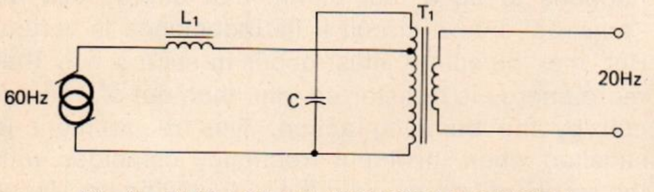

Fig. 9—THE LORAIN SUB-CYCLE RINGER
The production of a subharmonic as a direct consequence of circuit non-linearity is theoretically impossible. *Yet, this electromagnetic arrangement appears to accomplish such a result. Actually, the 20 Hz is the* difference frequency *between the 60 Hz input and an "internal" 40 Hz signal which is the 2nd harmonic of 20 Hz. The 40 Hz signal may be construed to be generated by the non-linear inductance of L1. By assuming the circuit to* already *be in operation, the interaction between the three frequencies maintains he operation—the 20 Hz is doubled to 40 Hz and the "mixing" of the 40 Hz and 60 Hz frequencies, in turn, yields the difference frequency, 20 Hz. L1 behaves as both "mixer" and "frequency multiplier".*

The electromagnetic circuit shown in fig. 9 is a simplified version of the Lorain sub-cycle ringer, once widely used in telephone work. Here, as with the device previously described, non-linear magnetics are exploited for a useful result. The intriguing thing about the sub-cycle ringer is that *frequency division* is achieved. This is apparantly contrary to the Fourier theorem, from which we can anticipate only higher harmonic frequencies from the interaction of an ac signal and a non-linear parameter, such as inductance. How does it then come about that a *sub-harmonic* of the impressed frequency is provided by this rather simple assemblage of passive components?

It happens that there is no way in which the mere condition of non-linearity can cause a fraction of an applied frequency to generated. Something special and unique must be done to bring about such "impossible" operation. Much insight into the true nature of the sub-cycle ringer can be attained by contemplating a somewhat analagous frequency divider known as a *regenerative modulator.* In the regenerative modulator the essential function blocks, and the signals needed to produce frequency division are clearly delineated. In the sub-cycle ringer, they are concealed. Fig. 10 shows a transistor regenerative modulator which, like the sub-cycle ringer, divides incoming 60 Hz down to 20 Hz. Our procedure in describing the theory of operation will be to assume that the circuit is *already* in operation, then to show why it continues to operate.

The input stage, Q1, has two inputs — 60 Hz is applied to its base, and 40 Hz is impressed on its emitter. Because this stage operates in a non-linear mode, the difference frequency, 20 Hz, is developed across its tuned output circuit. (Non-linearity is achieved by having the forward bias derive from the input signals, primarily the 60 Hz input, rather than from a dc source as is commonly done in ordinary class A amplification.) Some of the 20 Hz energy is available for the output, and some is capacitively coupled to the base of stage Q2. This stage is also operated as a non-linear amplifier. The tuned tank in its collector circuit selects the second harmonic (40 Hz) from the large number of harmonics of 2 Hz caused by the non-linear response of Q2. And, because this 40 Hz signal is "re-cycled" through stage Q1, the mixing and harmonic generatingaction continue, thereby keeping the circuit in operation. Note that, despite the non-linearity of the two stages, no actual frequency-division is (nor can be) accomplished within the circuit. Rather, the sub-input frequency delivered at the output terminals is the consequence of *heterodyne action.*

Returning now to the magnetic sub-cycle generator of fig. 9, an analagous reasoning applies to its operation. Although, L1 is not tuned, a 40 Hz signal is developed across is because of the non-linear inductance it offers to the 20 Hz signal produced in the tuned winding of T1. At the same time, L1 "mixes" the incoming 60 Hz signal with the 40 Hz component, and thereby provides 20 Hz pulses to T1, constantly replenishes its energy so that a constant 20 Hz output signal is available. As with the transistor circuit of fig. 10, no output exists without the 60 Hz input. Both circuits operate as "stimulated oscillators". But, because the magnetic sub-cycle generator has no internal amplification, it is not so readily made self-starting . A momentary short-circuit across L1 produces a large transient which provokes the circuit into operation. (Although not shown in the simplified schematic of fig. 9 the actual Lorain sub-cycle ringer used a relay to perform this shorting action during start-up.) For the experimentally inclined, there might be some interesting possibilities for an audio-frequency version of this system for c.w. signal processing at the output of a receiver. Permanent magnets and extra windings for d.c. will be found useful for attaining the requisite non-linearity of the cores.

A situation apparantly contrary to "common sense" exists in many electrical machines. In the d.c. generator, such as shown in the semi-schematic illustration of fig. 11, the rotating armature could produce no current in the load if the field flux were absent. By the same token, the stronger the field flux, the higher is the voltage developed across the load, and the greater is the current forced through it. Indeed, a rheostat, R_f, is commonly used to control the voltage and current delivered to the load. This is not less than reasonable considering the electromagnetic coupling which must exist between the field and armature windings. In view of the fact that a.c. is actually induced in the armature (and is subsequently rectifield by the commutator), it might appear that this electromagnetic coupling is similar to that in an ordinary transformer. But, how does one account for the fact that a change in load demand, say by varying R_l, does *not* cause any change in the field current, I_f? Here, as with the parametric converter, we find a strange departure from conventional transformer-action. In this case, however, we cannot attribute the behaviour to parametric phenomena.

The resolution of this dilemma stems from the recognition that the field and armature fluxes are spatially in a *quadradture* relationship — no mutual flux "links" the field and armature windings. So, contrary to a popular misconception, the electrical energy dissipated in the load is *not* derived from the energy stored in the magnetic field. This is fortunate, for otherwise it would not be practical to construct tachometers and other d.c. generators using permanent magnets, for the magnets would quickly "run down" — in analagous fashion to a battery. The true function of the field flux is merely to *deflect* the free electrons in the armature conductors so as to cause piling up of electrons at one end and a deficit at the other end. In more commonplace language, an EMF is induced in the rotating

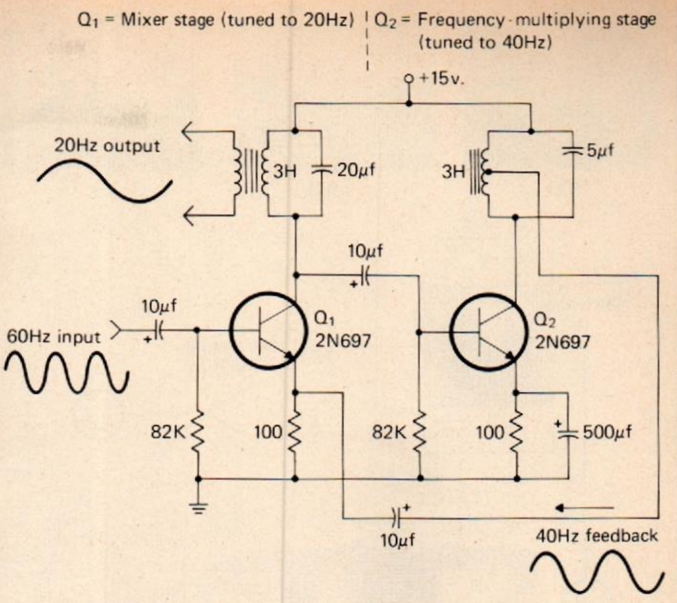

Fig. 10—AN ELECTRONIC CIRCUIT WHICH PRODUCES THE SAME RESULTS AS THE SUB-CYCLE RINGER
This circuit, known as a regenerative modulator, provides instructive insight because of the ease with which its functional blocks can be identified. Note that the 20 Hz output is not actually generated as a "subharmonic" of 60 Hz. Rather, the 20 Hz is a difference frequency, being the heterodyne between 60 Hz and 40 Hz. The 40 Hz signal is the 2nd harmonic of this 20 Hz heterodyne product. The operational sequence of this circuit is most easy to follow by assuming that it is already performing as described—then, it is readily seen that the three frequencies continue to interact to mainain operation.

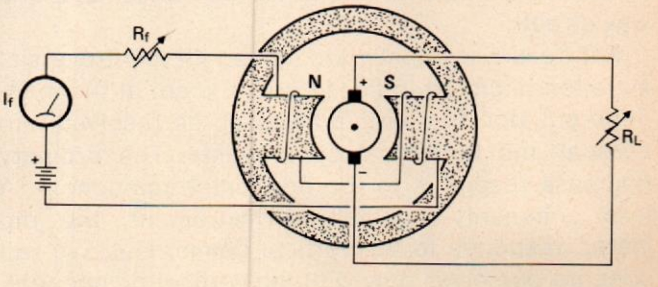

Fig. 11—THE DC GENERATOR—AN ELECTROMAGNETIC ENIGMA
The electromagnetic "coupling" between the field and armature windings is such that load current can be controlled by varying the field current but field current is not responsive to variations of load current.

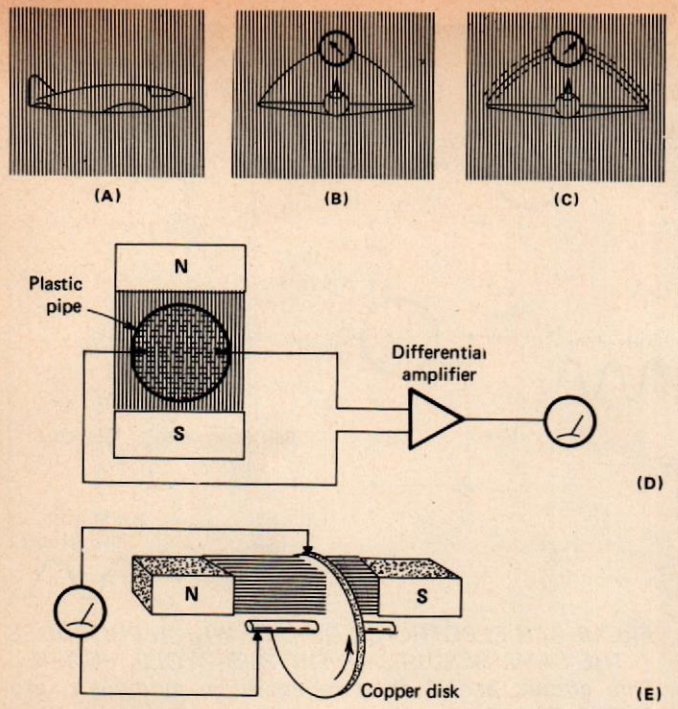

Fig. 12—ELECTROMAGNETIC FOOD FOR THOUGHT
Cutting the flux may not be "cut and dried."

(a) Side view of an aluminum-clad aircraft flying through the vertical component of the earth's field.
(b) Head-on view of craft flying through vertical component of earth's field. A detection device is deployed in order to measure the EMF generated in the wings.
(c) Same as (b), but the leads to the detector are magnetically shielded.
(d) Liquid-flow measuring system.
(e) The Faraday disk generator.

armature. This requires virtually no energy from the field. When current is demanded by a load, the requisite energy is supplied by the *mechanical driving system* because the generator then develops "motor action". From Lenz's Law, this motor action is in the opposite rotational direction from which the generator is being driven. In any event, the field circuit could care less — its deflective action of electrons in the armature conductors is as easily accomplished at heavy as at light armature loads.* And that is why the cause and effect relationship between field current and armature current is a one way street!

For *desert,* we finally are served the controversial situation depicted in fig. 12 abc. Except at the magnetic equator, the earth's field can be resolved into vertical and horizontal components. The ordinary compass responds to the horizontal component. A less commonly-encountered instrument, the dip meter, responds to the vertical component. We will concern ourselves only with the vertical component, and imagine it to comprise lines of force arrayed perpendicular to the surface of the earth. For the purpose at hand, it is not of any consequence whether the magnitude of this vertical flux is the same in a and b of fig. 12. We simply wish to ascertain whether the detector connected to the metallic wings will record a current or voltage proportional to the speed of the aircraft. Apparantly, this will not be the case in b because the leads associated with the detector would have the same EMF's induced in them as have the wings. So, no *net* voltage would be developed across the terminals of the detecting device. This suggests the technique shown in c wherein the detector leads are *magnetically shielded.* Will this strategem work?

In order to evade the barrage of letters which are surely destined to innundiate the author if either conclusion is cited, no direct answer will be given. However, some very suggestive clues may be ferreted from somewhat-similar electromagnetic situations:

In d of fig. 12, we see a practical arrangement for monitoring liquid flow in a pipe. If the amplifier has a high impedance, the fluid may even be a moderately good insulator. On the other hand, a fluid with good conductivity will generally make the task easier. (provided, there is no electro-chemical reaction at the probes) Here, we have a conductor "cutting" magnetic flux, even though the "conductor" is continuously replenished with the passage of time. The faster the flow, the greater is the induced EMF developed across the probes. Similarly, the Faraday disk generator of fig. 12e continuously supplies new conductor material so that the "cutting" of magnetic flux occurs without interruption. Consequently direct current is generated with no need for the rectifying action of a commutator. Can one meaningfully relate the situations depicted in (d) and (e) to that of (c)? In (d) and (e) we enjoy the luxury of a *confined* magnetic-field so that the detector leads have no EMF induced in them. Of course, we hope to accomplish the same result with the aircraft by *shielding* the detector leads. Also, in (d) and (e), the detector is in the same reference frame as the field. In the aircraft, the detector is in the same reference frame as the conductor. (the wings). Without splitting hairs, or bringing the principle of relativity into the picture, can we decide, in a qualitative may, whether the idea portrayed in (c) is feasable?

Whatever your evaluation, it is hoped you will decide you have been served a tantalizingly good meal and will be of a disposition to return for repeat orders! ■

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*Second order effects, such as armature reaction, are not considered here. For greater insight into the behaviour of electrical machines see the author's Howard W. Sam's book, "Electric Motors & Electronic Motor Control Techniques" No. 21340.

COIL-WINDING CHARTS

INDUCTANCE is only one of the characteristics that determines a coil's suitability in a specific application. Distributed capacity is equally important because it, along with inductance, determines self-resonant frequency of the coil, the point at which the coil becomes useless as an inductor. In fact, above its self-resonant frequency, any coil will act for all the world as if it were a poor capacitor, except that it will not block direct current.

This article will explain how to use the dimensions of a coil to predict its inductance, distributed capacity, and self-resonant frequency. Nomograms are included so that all "calculations" are performed simply by drawing straight lines across the scales.

Inductance

Inductance is the property for which coils are used in circuits, and distributed capacity is another property we must take into account in order to know the useful inductance available. Roughly speaking, inductance can be increased by increasing either the diameter of a coil or its number of turns.

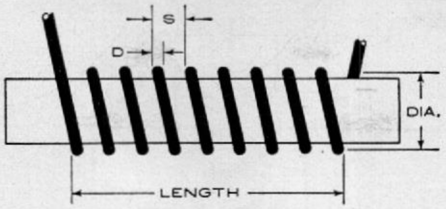


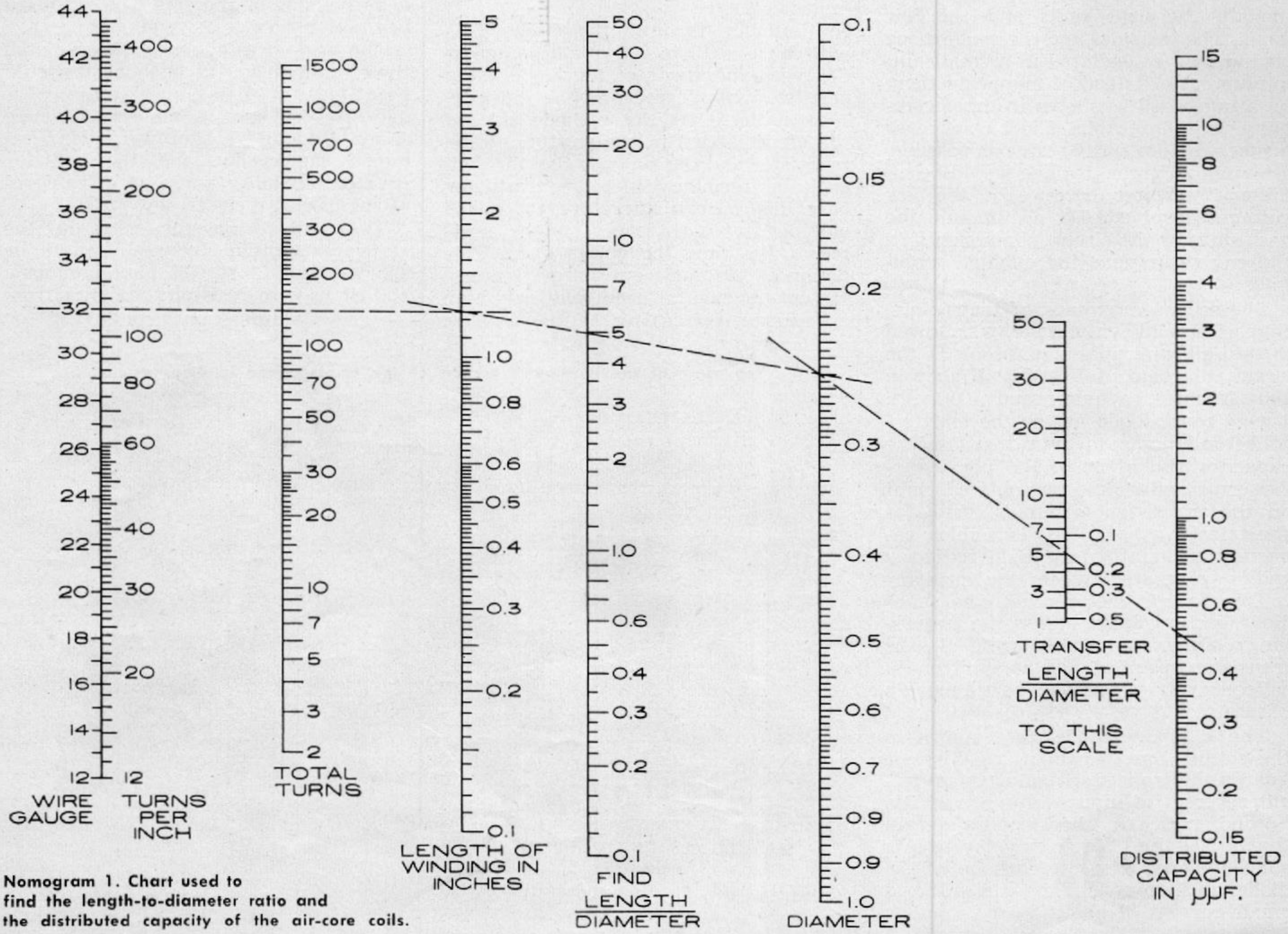
Fig. 1. Basic coil geometry used in charts.

Increasing the number of turns is more effective because inductance increases as the square of the number of turns. In other words, doubling the number of turns will increase the inductance by a factor of four, tripling the number of turns will increase the inductance by a factor of nine, and so on.

However, many of the changes made to increase inductance will also increase distributed capacity, and the over-all effect is to reduce the self-resonant frequency at a rapid rate. We can consider a practical coil as consisting of an ideal coil (pure inductance, and no capacity) in parallel with an ideal capacitor, and therefore increasing either one will reduce the resonant frequency according to $f = 1/(2\pi\sqrt{LC})$. It is desirable, then, to have independent control over both inductance and distributed capacity. To a certain extent, such control is available to those who wind coils, through manipulation of the coil's silhouette. A series of 20-microhenry coils can be made, ranging from long and thin ones to short and fat ones. Although each coil has the same inductance, the different silhouettes will dictate that they have different values of distributed capacity and therefore different values of self-resonant frequency.

Distributed Capacity

Dependence of distributed capacity on coil dimensions is not as straightforward as inductance is, but there are a few general rules to serve as guides. Coils that range from short (those whose diameter is greater than the length) to medium (those whose length is two or three times the diameter) will just about double their distributed capacity when the diameter is doubled. In longer coils, up to those whose length is 50 times the diameter, there is very little dependence on di-



Nomogram 1. Chart used to find the length-to-diameter ratio and the distributed capacity of the air-core coils.

ameter. Beyond that, we have the very long coils, where there is a definite *reduction* in distributed capacity as the diameter is *increased*.

The length of a coil has an effect on its value of distributed capacity, but the number of turns within a certain length has very little effect. For instance, a coil one-inch long could be wound with 24 turns of No. 18 wire, or it could be wound with 92 turns of No. 30 wire, but the distributed capacity will be about the same in both cases. This is a means of exercising separate control over inductance and capacity because you can take an existing coil design and switch to a finer size wire. This will allow you to put more turns in the same length, having little effect on distributed capacity but increasing inductance by the square of the added turns.

These statements will prove helpful as long as you realize that they apply only in a very general way and are on the lookout for exceptions. The nomograms will give numerical answers which are adjusted to take care of exceptions to these generalities.

Usually, the goal is to wind a coil with

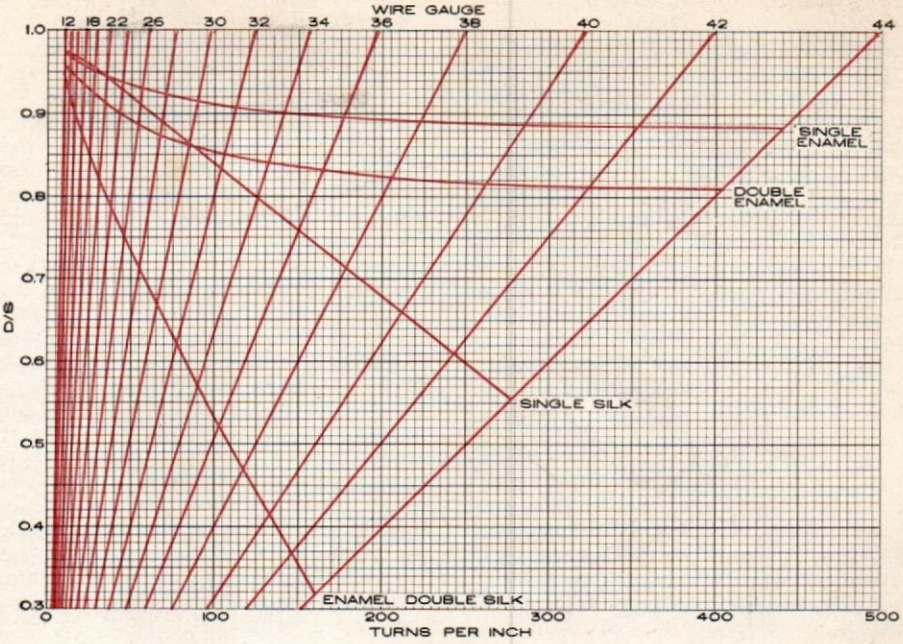
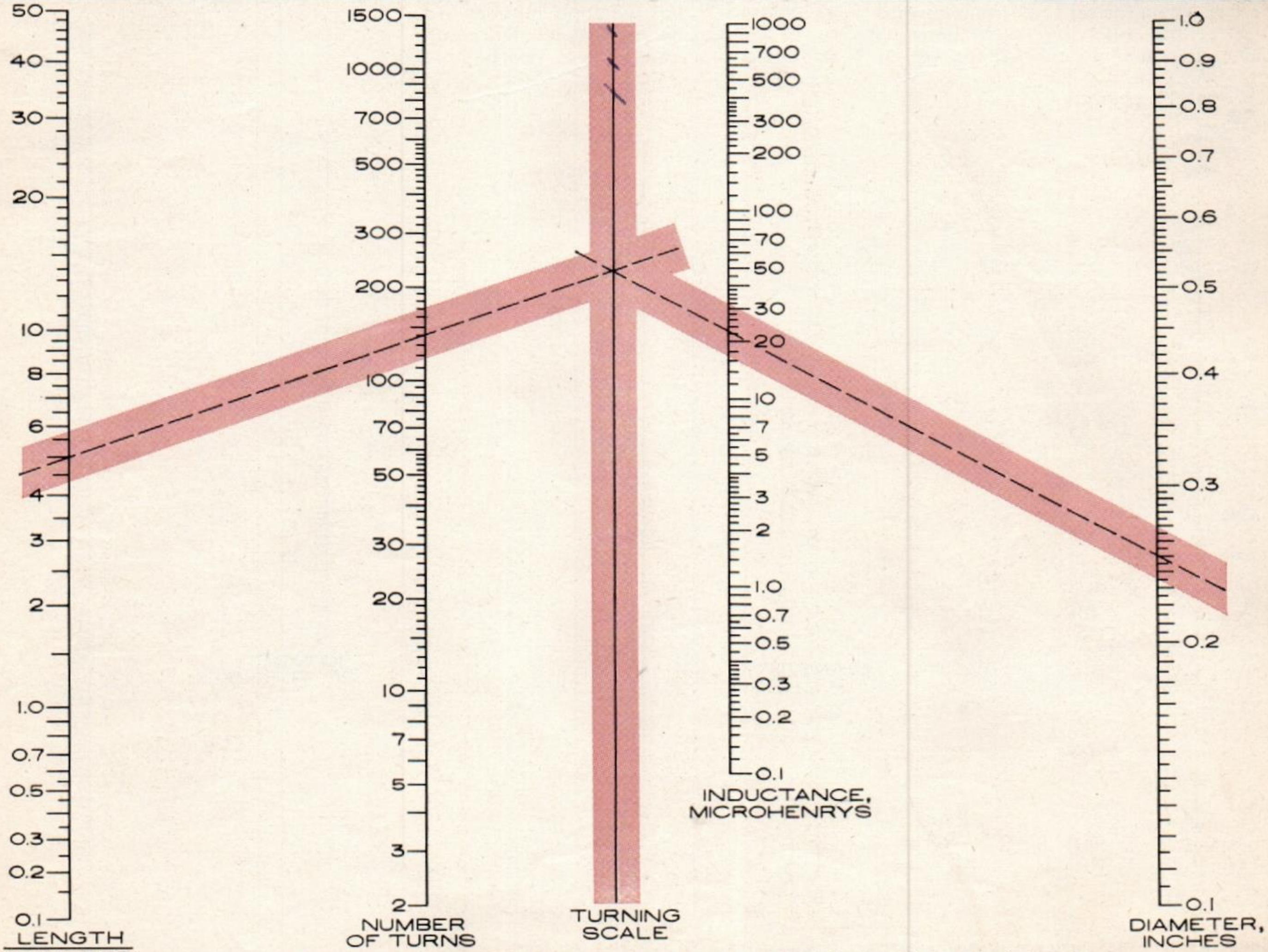


Fig. 2. The number of turns per inch for wire having various types of insulation.

Nomograms for determining the inductance, distributed capacitance, and the self-resonant frequency of coils.

By **DONALD W. MOFFAT**



Nomogram 2. By using this chart, the inductance values of air-core coils of the sizes shown may be found.

as little distributed capacity as possible. Even when a fair amount of capacity is acceptable, it should be controlled and its value known so that the coil will be compatible with the rest of the circuit. If minimum distributed capacity is the goal, the ideal coil is fatter than it is long, having a diameter about one and a quarter times its length. Unfortunately, this is not the most convenient shape to fit into an electronic chassis and it may be necessary to accept more than the minimum amount of capacity and arrive at a compromise coil shape. One advantage to the nomograms is that they make it easy to investigate various possibilities, as will be explained shortly.

Coil Resistance

Every coil must have some resistance, which will determine the *"Q"* factor. However, this factor determines just the sharpness of resonance and has very little bearing on the actual frequency of resonance. Since this article is restricted to an investigation of the interaction between inductance and distributed capacity, it will be assumed that the results are independent of coil resistance.

Computations

One of the most important factors in single-layer coils is the length-to-diameter ratio, which is used in the computations to follow. This ratio is found on Nomogram 1 and then is used as the first entry on the other two nomograms.

After the following instructions for using the nomograms, a simple numerical example will be presented.

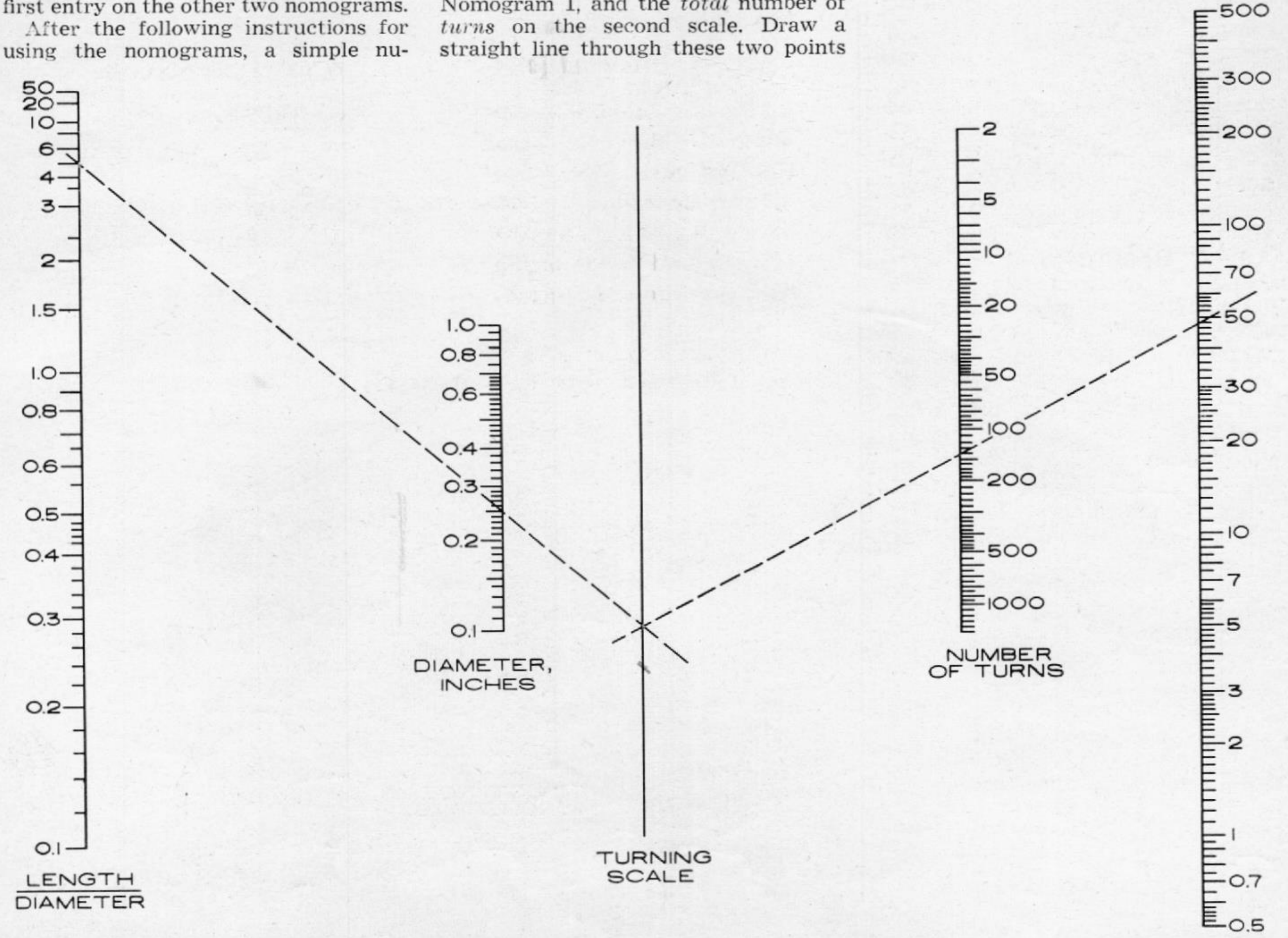
Distributed Capacity: Nomogram 1 is used for finding both the length-to-diameter ratio and the distributed capacity.

There are two sets of numbers along the first scale. *Turns per inch,* on the right-hand side of the scale is the basic number that is used for computations, and can always be used. The left-hand side of the scale, *wire gauge,* is for convenience in the unique but common case where single enamel wire is used and there is no spacing between turns. For any other situation, the graph, along with Fig. 2, can be used to arrive at a value of turns per inch. If the windings are closely spaced, follow the line for the type of insulation out to where it crosses the line for wire gauge and at that crossing note the number of turns per inch. For instance, the line for No. 36 wire crosses the line for single silk insulation at 150 turns per inch. If the turns are not wound as close as possible, but have some space between them, determine the values of D and S (see Fig. 1) and then on Fig. 2 follow that line out until it crosses the line for wire gauge, at which point you will read the turns per inch. Remember that S in the figure includes the insulation over the wire, a quantity that becomes increasingly important for fine wires.

Once *turns per inch* is determined, locate that value on the first scale of Nomogram 1, and the *total* number of *turns* on the second scale. Draw a straight line through these two points and extend it to cross the third scale, where you will read the *length of winding*. The actual value at this crossing is not important, as it is only the *point* of crossing that is going to be used for drawing the next line. On the other hand, if you knew the length of the coil, it would not be necessary to perform this first computation; simply locate that value on the *length* scale, and you are ready for the next step.

Next, locate the correct value on the *diameter* scale, and draw a straight line from that point to the indicated point on the *length* scale. Where that line crosses the middle scale, read a value of *length/diameter*, a value that will be used for each of the other computations. As with the length of the coil, this step does not have to be performed if the value is known, or if its computation can be done mentally. For instance, if your coil has a half-inch diameter and is one inch long, it is not necessary to draw the lines to determine that the ratio *length/diameter* is two.

The last step in determining distributed capacity starts with locating, on the next to the last scale, the value which was found for length/diameter. Diameter has already been located on its scale. Draw a straight line through these two points and extend the line to cross the last scale. Now read the appropriate value of *distributed capacity*.



Nomogram 3. Chart employed to determine the self-resonant frequency of air-core coils from the number of turns and the size.

Notice the peculiar layout of the sixth scale, to which the value of length/diameter was transferred. Numbers go down from 50 to about 1 and then the rest of the scale, down to 0.1, is folded back on itself, so that some spots on the scale are used as the location of two numbers. Another point of interest is that numbers at the lower end of the scale are quite crowded together, meaning that any ratios in this range will give about the same amount of distributed capacity. Almost no accuracy would be lost by saying that any value of length/diameter between 1.2 and 0.6 is to be transferred to a location "near" the lower end of the scale.

Inductance: Once *length/diameter* has been determined from Nomogram 1, locate that value on the first scale of Nomogram 2, and locate *number of turns* on the second scale. Draw a straight line through these two points, extending it to cross the third scale. On the last scale, locate the correct value of the *diameter*. Then a straight line drawn from that point to the point where the first line crossed the *turning scale* will cross the fourth scale at the *inductance* of the coil.

One of the advantages to the use of nomograms can be illustrated at this time. If the inductance that is found is not the desired value, you can rotate a straight-edge about the crossing on the *turning scale* until it passes through the desired inductance. The straight-edge will then cross the *diameter* scale at the diameter necessary to give that inductance. You can then work the first nomogram backwards to find a new *length of winding,* and the coil is redesigned for the required inductance.

Self-resonant Frequency: Once *length/diameter* has been determined from Nomogram 1, locate that value on the first scale of Nomogram 3, and locate the *diameter* on the second scale. Draw a straight line through these two points, extending it to cross the third scale. On the fourth scale, locate the correct *number of turns,* and draw a straight line through that point and the point where the first line crossed the *turning scale*. Extend that line to the last scale, where it will cross the self-resonant *frequency* for that coil.

Any coil is normally designed to operate at frequencies below self-resonance, where it has a useful inductance. At frequencies above self-resonance, nothing can be added to make the circuit resonate.

As with any other nomogram, it is easy to rotate a straight-edge about any point to see the effects of changing one or more of the numbers.

Example

In order to be certain the instructions are clear, let's run through it again, with numbers. Suppose you have 140 turns of No. 32 enameled wire on a quarter-inch form. On Nomogram 1, locate 32 on the right-hand side of the first scale and 140 on the second scale. A straight line through these two points will cross the third scale at 1.25, the *length of winding*. Next, locate 0.25 (quarter inch) on the *diameter* scale and draw a line from that point to 1.25 on the *length* scale. It was not necessary to note that the length was 1.25 because that value is not used in any of the other computations and only the location of the crossing on that scale is important to further computations. A straight line drawn through these two points shows that the *length/diameter* ratio is 5. Locate 5 on the next to last scale and draw a line from 0.25 on the *diameter* scale, through 5 just located, and this line will cross the distributed capacity scale at 0.51 μμf.

Now, use Nomogram 2 to find the inductance. From 5 on its *length/diameter* scale, to 140 on its *number of turns* scale, draw a straight line and extend it to cross the *turning scale*. Draw another line from that crossing to 0.25 on the *diameter* scale and the answer of 22 microhenrys is found on the *inductance* scale.

Self-resonant frequency is found on Nomogram 3. Draw a straight line from 5 on the *length/diameter* scale to 0.25 on the *diameter* scale and extend it to cross the *turning scale*. From that point of crossing on the *turning scale,* draw a line through 140 on the *number of turns* scale and extend it to cross the last scale. At that last crossing, read a self-resonant frequency of 48 megacycles.

Accuracy

Several equations have been developed for computing the characteristics of a coil. Unfortunately, we do not have universal agreement on a single correct set of equations, each one seeming superior for different purposes. These nomograms have been based on equations that have been supported experimentally over the ranges of values used for the scales.

Coil leads, even though only a piece of straight wire, have both inductance and capacity that add to those of the coil proper. In fact, a straight piece of wire has a self-resonant frequency. For these nomograms, it has been assumed that there are no leads on the coil, an assumption that introduces negligible error until the coil is operating at frequencies of hundreds of megacycles and above. You can generally figure that the calculated value of self-resonant frequency is the maximum possible, and in the actual circuit, the coil will resonate at some lower frequency; some safety margin should always be allowed.

Usually, the number of turns cannot be determined precisely because the last turn does not have a definite ending, but tapers away from the rest of the winding. At least some part of the last turn (and of the first turn) is more of a lead than a part of the coil proper. Sometimes the last turn is wrapped around a terminal or a pigtail and soldered in place. Any wraps not shorted by solder will form another little coil, the characteristics of which will add to those of the main coil.

Weather conditions, such as temperature and humidity can have a noticeable effect on the characteristics of a coil, especially if sufficient and constant tension was not maintained during the winding.

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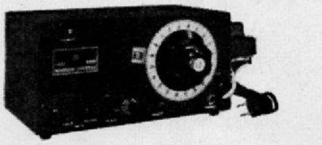

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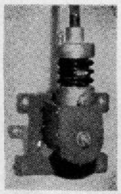

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6 MFD	600 VDC	.85	4 MFD	4000 "	12.95
8 MFD	600 VDC	.95	1 MFD	5000 VDC	4.50
10 MFD	600 VDC	1.19	2 MFD	5000 VDC	8.50
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8 MFD	1000 VDC	1.95	2 MFD	12,500 "	34.50
10 MFD	1000 VDC	2.50	1 MFD	15,000 "	42.50
12 MFD	1000 VDC	2.95	2 MFD	16,000 "	69.50
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Although the example used a quarter-inch coil form and we used 0.25 on the *diameter* scale, diameter is really meant to be taken to the center of the wire. For fine wire, the difference between the diameter of the coil form and the diameter to the center of the wire is too small to have any bearing on the answer. However, when using heavy wire on a coil form of small diameter, the accuracy can be improved by adding the diameter of the wire to the diameter of the coil form.

The nomograms have been based on air-core coils because the use of other material introduces several other variable conditions. Modifying the charts just to provide for the effects of slugs would complicate them to the point where their usefulness would be questionable. With air-core coils, however, considerable time and effort can be saved by using the charts. ▲

HI-LO VOLUME CIRCUIT

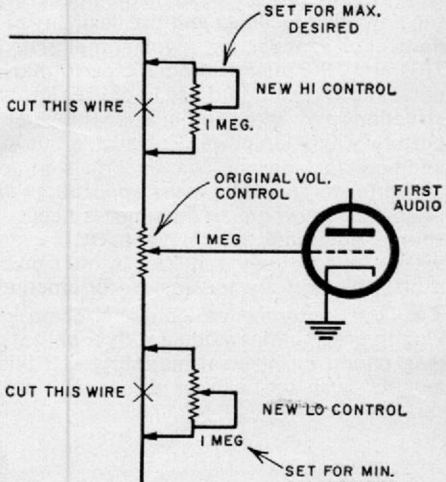
By L. M. DILLEY

WHILE on a service call at an Old Peoples' Rest Home, I was asked by the superintendent to help him solve a problem. It seems that some of the patients who were hard of hearing would increase the volume on the TV set more than was really necessary. A second group, whose hearing was more nearly normal, would then retaliate by turning the volume control to the other extreme. This, of course, was the cause of continual bickering with the result that none of the patients could enjoy a program.

After some thought I came up with a solution to their difficulties which may be equally applicable in private homes where there are Senior Citizens and children in the same household.

The solution lies in the inexpensive and relatively simple circuit shown in the diagram below.

The only parts needed are two extra volume controls of approximately the same resistance as the original volume control. These should be mounted on the TV chassis in close proximity to the regular control but in such a location that they are inaccessible and therefore tamper-proof. In this way the maximum and minimum volume levels are fixed although, psychologically, the user thinks he has complete control of the volume level. ▲



COIL-WINDING NOMOGRAM

By A. L. TEUBNER / *Designing single-layer air-core inductors for use in transmitter tanks, loading coils, and matching networks is simplified by employing this easy-to-use chart.*

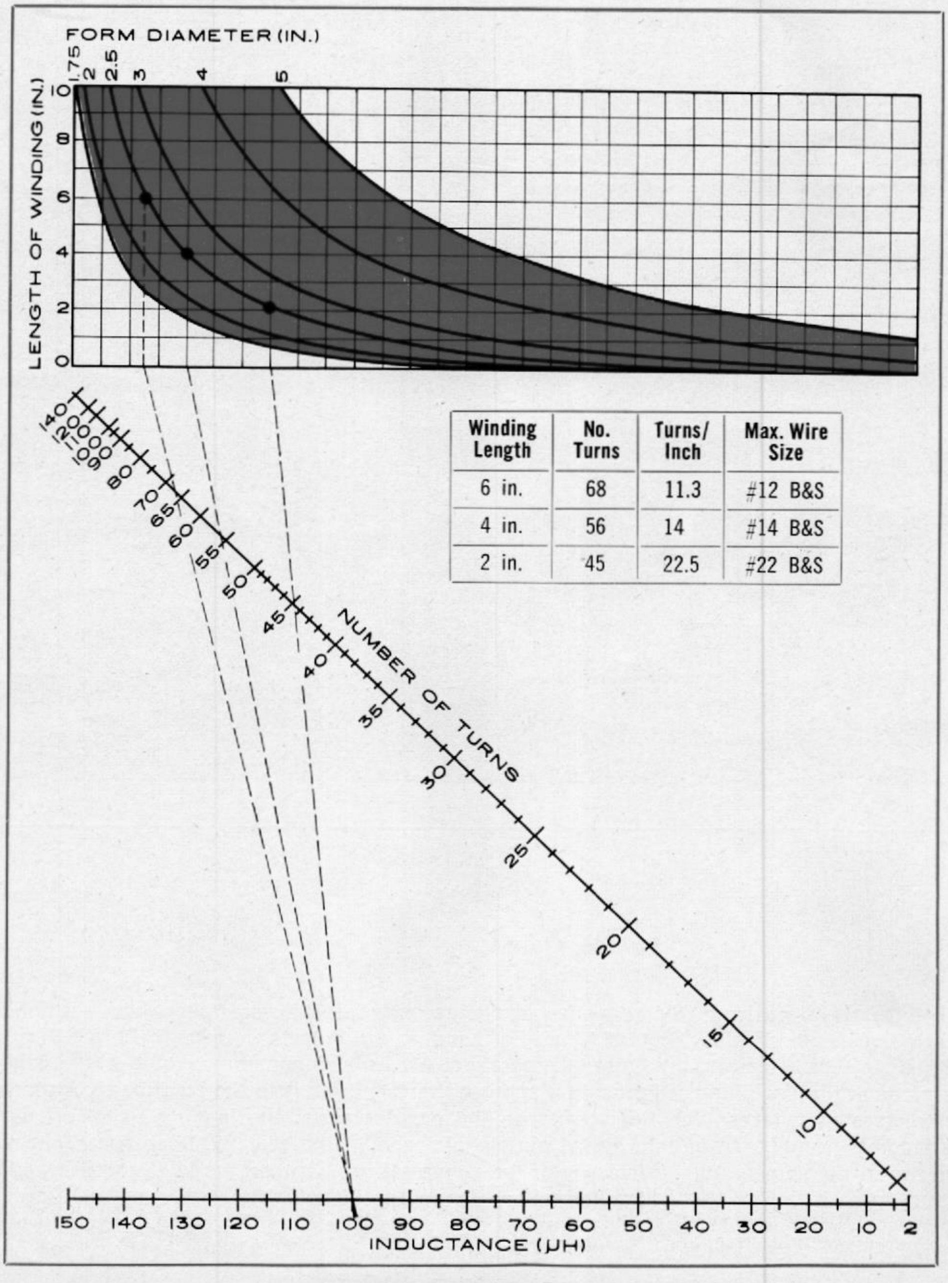
THIS nomogram was constructed to eliminate much of the pencil pushing involved in designing single-layer inductors in the range of values normally required for amateur transmitters, loading coils, and feedline matching networks. Since inductance, for a given form diameter, is related to both the number of turns and the winding length, the number of combinations of these two is limited only by the form length, at one extreme, and the minimum desirable wire size, at the other. This diagram makes it easy to discover the available range and to strike a good compromise. It can also be used in reverse to calculate the inductance of a "junk-box" coil. The scales are based on a simple approximation formula for single-layer air-core coils which should give sufficiently accurate results for radio-amateur use up through ten meters.

The formula employed is: $L=a^2n^2/(9a+10b)$ where L is the inductance in μhy., a is coil radius in inches, b is coil length in inches, and n is the number of turns.

As an example of the design problem using the nomogram, assume that you need a 100-μhy. loading coil, and have on hand a 2½" diameter form, 6" long. On the nomogram, find the point where the curve corresponding to a diameter of 2½" crosses the line for 6" of length. From this intersection project downward to the bottom edge of the graph portion. Then connect the point just found to the 100-μhy. mark on the inductance scale, using a straightedge. The point where the straightedge crosses the center scale gives the number of turns, in this case 68. Repeating the procedure for lengths of 4 and 2 inches yields 56 and 45 turns, respectively.

After dividing length by turns, we refer to a copper-wire table and find that the largest sizes of enamelled wire that we can use are Nos. 12, 14, and 22, in order of decreasing winding length. These results are summarized in the table. The final choice will be influenced by such things as the expected r.f. current and potential gradient, and the desired "Q" of the coil.

Calculating the inductance of an existing coil follows the same general procedure, except that the point on the horizontal axis corresponding to length and diameter is connected with the known number of turns, and a straightedge will lie on the inductance value. Since the nomogram was designed for the reverse problem, some combinations may not fall on the inductance scale. ▲



Winding Length	No. Turns	Turns/ Inch	Max. Wire Size
6 in.	68	11.3	#12 B&S
4 in.	56	14	#14 B&S
2 in.	45	22.5	#22 B&S

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By RUFUS P. TURNER

A pair of miniature transistor driver transformers may be connected together to form saturable reactor.

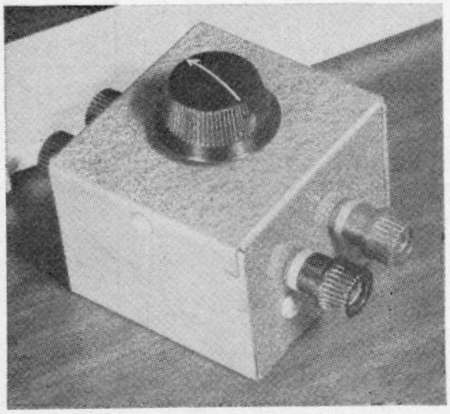
TWO miniature transistor driver transformers may be connected to provide an inexpensive saturable reactor and with low d.c. input the inductance may be varied from 2.8 to 20 henrys. The d.c. resistance is 800 ohms. Fig. 1A shows the arrangement in which the 20,000-ohm primary windings are connected in such a way that any a.c. induced in the two 1000-ohm windings is cancelled and does not appear in the battery circuit. The transformers are *Lafayette* No. AR-104, although the same principles could be applied to other transformers.

A 3-volt battery (two size D flashlight cells in series) supplies adjustable d.c. to the secondaries as the control winding through a 10,000-ohm, 5-watt TV-type rheostat. Fig. 1B shows variation of inductance from 2.8 to 20 hy. as current is varied from zero- to 20-ma.

The parts are conveniently mounted in a 2" x 2¼" x 1¾" aluminum utility box. Any convenient shield can also be used.

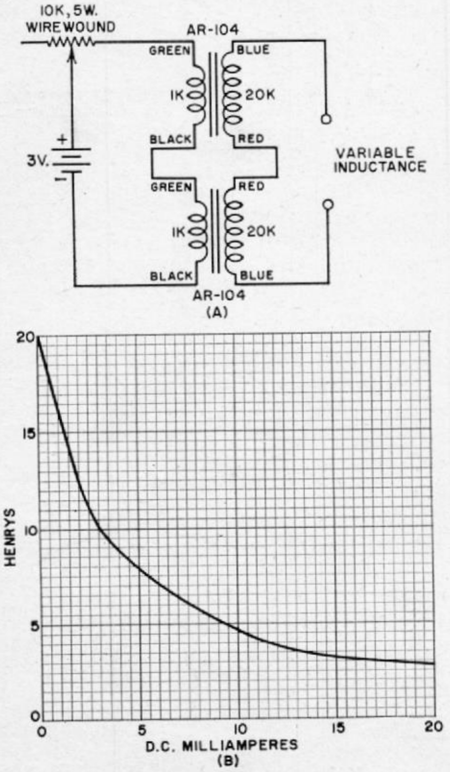
There are many obvious uses for a small variable inductor of this sort having the high inductance and better than 7:1 range it provides. One of these is the audio-frequency *LC* circuit tuned by varying *L*. Fig. 2A shows such a circuit used to peak the response of an a.c. v.t.v.m. or oscilloscope as a bridge null detector. The 0.003-µf. mica capacitor allows the circuit to be peaked to 1000 cps with 5-ma. control current. As shown in Fig. 2B, the 0-ma. peak is 640 cps and the 10-ma. peak, 1500 cps.

The same circuit has been employed as a d.c.-tuned audio-frequency meter with the rheostat dial calibrated in cps and various capacitances switched in to change bands into the 20-15,000-cps range. The variable inductor has also been used in a bridged-T network in a feedback-type bandpass amplifier. ▲



Parts are mounted in small utility box.

Fig. 1. Circuit diagram and performance.



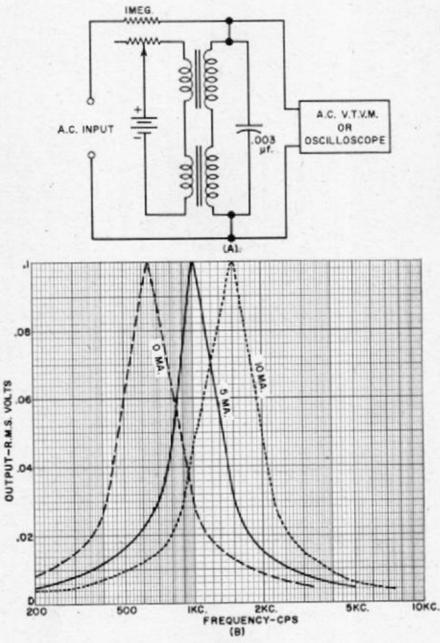
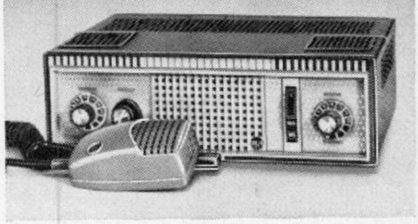


Fig. 2. Null-detector circuit application.



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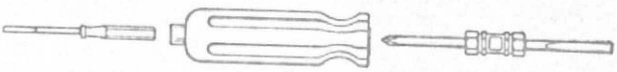

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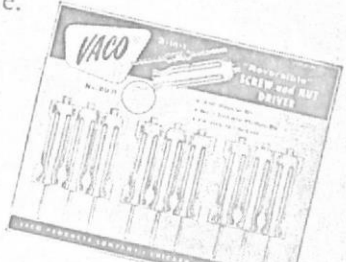

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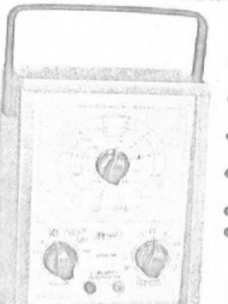

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Find the R, L and Z of IRON-CORE COILS

An ac voltmeter, a known resistor and a pencil and paper are all you need

By PAUL GHEORGHIU

THERE are several ways of measuring the resistance, inductance and impedance of an iron-core coil. Most of them require test instruments which may not always be on hand. This simple graphical method needs only a standard ac voltmeter, a single resistor, an ac source and a sheet of graph paper. The principle is not new, but seems to be little known.

Let's use as our example a choke whose R, L and Z are unknown. If we connect a pure resistance in series with it, we get an R-L circuit (Fig. 1).

Neglecting the dc resistance of the coil for the time, we measure voltage V_1 across the known resistor, V_2 the voltage across the choke and V_3 the source voltage. We can represent this in vector form by constructing a triangle with the voltages as edges (Fig. 2).

To construct the triangle, pick a convenient scale for voltage—one that will keep the triangle on the paper. Using the voltage across the resistor (V_1) as the horizontal reference, draw line OA equal to V_1. Using O as the

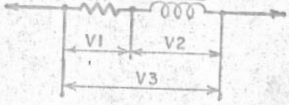
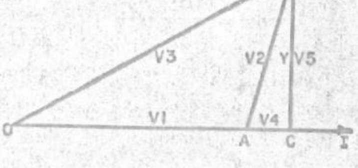


Fig. 1—Choke in series with fixed resistor. Voltage drops are indicated.

Fig. 2—Construction for finding R, L and Z.



center draw an arc with radius V_3. Then, using A as the center, draw another arc with radius equal to V_2. These arcs intersect at point B. From B, where the two arcs intersect, draw a perpendicular BC. Now AC and BC represent the voltage drops in the choke's resistance and inductance respectively.

Since the same current flows through the choke and resistor (we neglected the dc resistance of the choke), we get the coil resistance (R_2) and its inductance with the formula: $R_2 = \frac{V_4}{I}$

But since $I = \frac{V_1}{R_1}$, we can substitute $\frac{V_1}{R_1}$ for I and get $R_2 = \frac{V_4R_1}{V_1}$.

$L = \frac{V_5}{\omega I}$ or $\frac{V_5R_1}{\omega V_1}$ where $AC = V_4$, $BC = V_5$ and $\omega = 2\pi f$ (314 for 50 cycles, 377 for 60).

Once we have values for R and L we can calculate Z with the standard formula: $Z = \sqrt{R^2 + (\omega L)^2}$.

Example 1:

Calculate R, L and Z for the following values:

$V_1 =$ 50 volts (across resistor)
$V_2 =$ 113 volts (across coil)
$V_3 =$ 120 volts, 60 cycles
(2,500-ohm resistor in series with coil)

After construction (Fig. 3), the answer is:

$V_4 = 11$ volts $V_5 = 112$ volts

$$R_2 = \frac{V_4R_1}{V_1} = \frac{11 \times 2{,}500}{50} = 550 \text{ ohms}$$

$$L = \frac{V_5R_1}{\omega V_1} \text{ or } \frac{112 \times 2{,}500}{377 \times 50} = 14.9 \text{ henries}$$

$$Z = \sqrt{R^2 + (\omega L)^2} = \sqrt{550^2 + (15 \times 377)^2} = 5{,}685,$$

or approximately 5,700 ohms

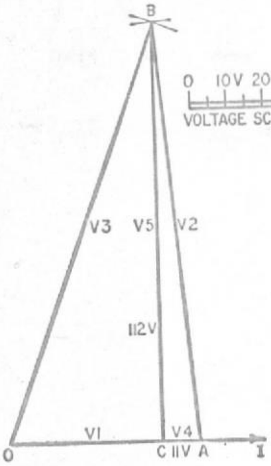


Fig. 3—Construction for example 1.

Example 2:

Calculate the R, L and Z of a choke connected in series with a 1,000-ohm resistor. The series hookup is supplied with 120 volts ac at 50 cycles. Voltages across the resistor and choke are 80 and 66, respectively. Construction is

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$V_4 = \sqrt{V_2^2 - V_5^2}$

$R_2 = \frac{\sqrt{V_2^2 - V_5^2}\, R1}{V_1}$

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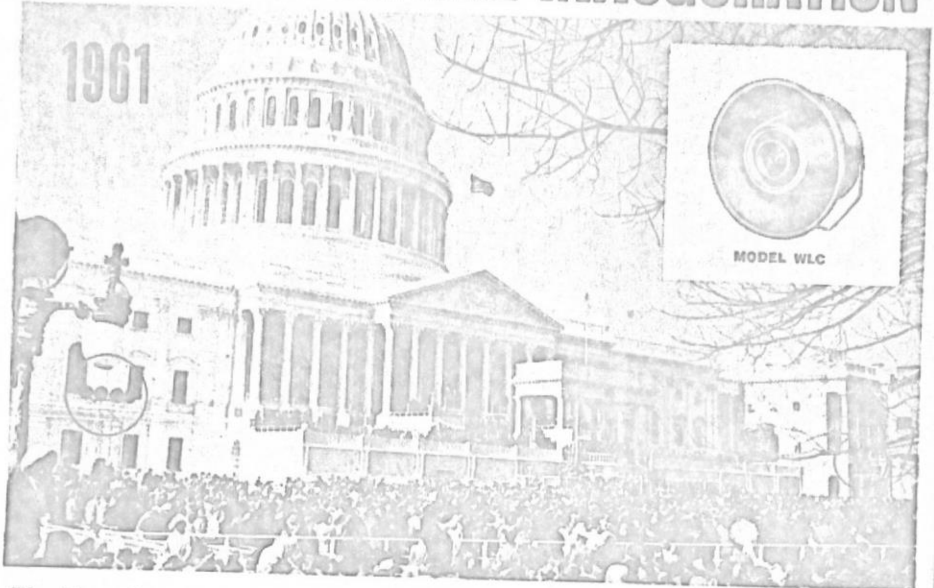

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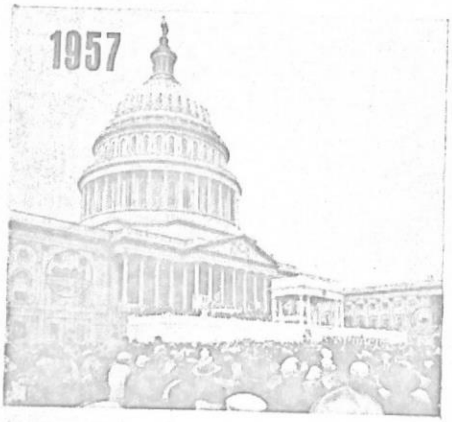

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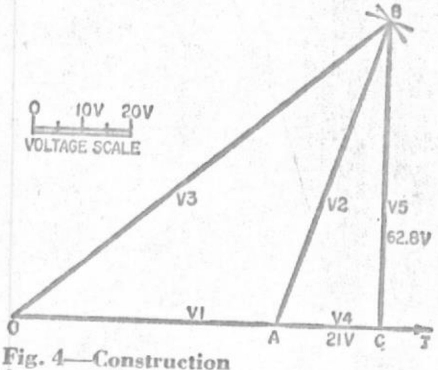

Fig. 4—Construction for example 2.

shown in Fig. 4. The triangle answer is: $V_4 = 21$ volts $V_5 = 62.8$ volts.

$$R = \frac{V_4R_1}{V_1} = \frac{21 \times 1{,}000}{80} = 262.5 \text{ ohms}$$

$$L = \frac{V_5R_1}{\omega V_1} = \frac{62.8 \times 1{,}000}{80 \times 314} = 2.5 \text{ henries}$$

$$\begin{aligned} Z &= \sqrt{R^2 + (\omega L)^2} \\ &= \sqrt{(262.5)^2 + (2.5 \times 314)^2} \\ &= 827.7 \text{ ohms.} \end{aligned}$$

Or approximately 825 ohms.

The degree of precision of this method depends on the relative value of resistance and reactance in the circuit as shown by the vector triangle.

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