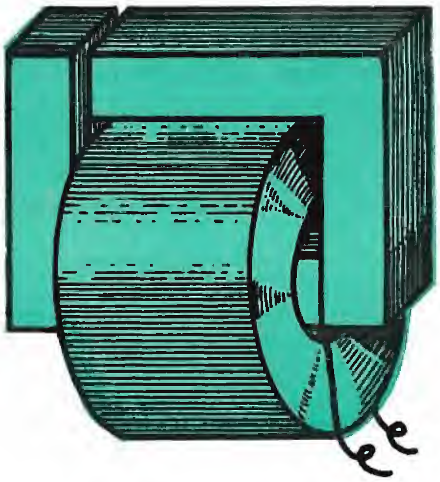

Power Inductors

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How to select the proper iron-core choke for power-supply filtering, as a charging choke for pulse networks, and for interference reduction.

INDUCTORS used in electronic power circuits are characterized by high induction levels, relatively large air gaps in the core, and larger size than other inductor types. Applications for power inductors include: (1) filter reactors for rectifier circuits, both input and smoothing types, (2) charging inductors for pulse networks, (3) interference reduction filters as found in "A+" lines of mobile equipment, and (4) saturable reactors used in some types of control circuits.

Power-supply filters make up a large percentage of power inductor applications, and the considerations necessary for these circuits are much the same as for the other types mentioned.

The important considerations for inductors used in power-supply filter circuits are fewer and more straightforward than for many other inductor applications. An exception, perhaps, is the effects of superimposed direct current in the coil. One of the reasons for this relative simplicity of specification is that power chokes are normally used at a single frequency, that is, the available a.c. power-line frequency, or twice that in the case of full-wave rectification. These frequencies range from 25 Hz in a few countries to the 400 Hz encountered in military aircraft and some shipboard equipment. Thus, it can generally be assumed that the entire frequency range is below 1000 Hz, which virtually eliminates the need for considering such high-frequency parameters as the effects of distributed capacitance and self-resonance.

Rectifier filter circuits may be divided into two groups, depending upon whether a choke or capacitor is used as the first component following the rectifier. Choke-input filters are preferred in cases where good regulation and low surge currents through the rectifiers are important to the power-supply design. The d.c. voltage from a given a.c. source is lower than can be obtained with a capacitor-input filter; however, more current is available from the same source by using the choke input because of the lower current peaks and r.m.s. heating factor.

It is important to use a choke with sufficient inductance to maintain current flow through one leg of the rectifier circuit at all times. There are many formulas for determining the minimum or critical inductance, which usually results in a value (in henrys) approximately one-thousandth the effective load resistance (in ohms) at minimum load.

Many power supplies are designed for use at a single d.c. output current level. In such cases, finding the value of critical inductance is fairly simple. Typical inductance values range from 2 to 25 henrys. In other supplies, the load current may vary over a wide range of values. *Swinging chokes* are often used in such applications, especially in transmitter power supplies where the output current varies from bleeder current to fairly large values only when the transmitter is keyed. The inductance of these chokes drops off rapidly with an increase in direct current through the coil. A typical swinging choke may have an inductance rating of 5:1 for an increase in current of 10:1. For example, the choke may have an inductance of 25 henrys at 20 milliamperes and drop to 5 henrys at 200 milliamperes. In this way, the choke "adjusts" itself to at least the minimum inductance for all current values.

A second choke, called a *smoothing choke,* is often incorporated in an additional filter section to reduce ripple further than can be economically accomplished with a single input filter. The value of inductance for this choke depends upon the input ripple and the desired amount of ripple reduction for the filter stage.

Charging inductors are used in the charging circuits of pulse-forming networks of radar equipment. They are similar in design and specifications to filter chokes. The inductance value is selected so that the circuit will resonate at one-half the pulse repetition rate. Charging inductors differ from filters in that much higher a.c. flux densities are encountered in charging inductors. Design considerations must sometimes take this into account.

Electrical Characteristics

Most power inductors have a direct current in the winding as well as the a.c. voltage across the terminals. The formula for inductance of an iron-core inductor with superimposed direct current may be stated as follows:

$$L = \frac{3.2\,N^2\,A_c \times 10^{-8}}{l_g + (l_c/\mu_\Delta)}$$

where L is the effective inductance in henrys, N is the number of turns, A_c is the net cross-sectional area of the core in square inches, l_g is the total length of the air gap in inches, l_c is the mean magnetic path length of the core in inches, and μ_Δ is the incremental permeability of the core material.

The factors in the numerator are straightforward and can be easily understood. The denominator of this equation represents the effective magnetic path length. This effective length is the total length of the air gap and core path lengths divided by their respective permeabilities. (The permeability of the gap may be regarded as unity; therefore, the effective length is that of the gap.) In many cases, the design of a reactor is determined to a great extent by the correct proportioning of these two lengths. *Incremental* or *effective permeability* (permeability when an alternating magnetizing force is superimposed on a direct magnetizing force) depends upon the characteristics of the core material, the d.c. magnetizing force set up in the core, and the amount of a.c. flux in the core. Data on permeability is not readily available and is best obtained from the core manufacturers' charts which plot effective permeability against d.c. magnetizing force and a.c. flux density. (See Fig. 1.)

Effective permeability decreases with an increase in d.c. magnetizing force in the core and reduces the effective inductance of the choke. Air gaps may be placed in the magnetic path to absorb some of the d.c. flux, thus reducing the effects of the direct current in the winding. A graph illustrating the effects of d.c. in a typical filter reactor is shown in Fig. 2.

Inductors carrying direct current may be classified as one of two types, *linear* or *non-linear*. Linear reactors are designed with an air gap greater than the effective length of the core (l_c/μ_Δ). As the permeability of air and the length of the gap are constant, the inductance of the choke will be fairly linear across the range of direct current in the coil.

Non-linear inductors, commonly called *swinging chokes*, are often used when the direct current from a power supply must vary over a wide range of values. They are designed so that a change in direct current will have a definite effect on the inductance. This is done by using little or no air gap so that l_g is small compared with (l_c/μ_Δ). Thus, the inductance of the reactor is determined largely by the incremental permeability of the core which decreases with an increase in direct current.

Under normal conditions, the d.c. flux in a filter reactor is much greater than the a.c. flux. For example, filter chokes are usually tested at an a.c. level of 5 to 10 volts and the rated direct current. This typically results in an a.c. flux density of 300 to 1000 gauss and a d.c. flux density of 12,000 to 14,000 gauss. If the a.c. flux were to be substantially increased on an inductor of this type, the total flux could reach the saturation level of the core material, resulting in low inductance, non-linearity, and poor filtering in power-supply circuits. For this reason, the a.c. voltage must be specified in inductor performance requirements. In 60-Hz single-phase full-wave rectifiers, the effective a.c. voltage at the choke input is approximately 50% of the d.c. voltage.

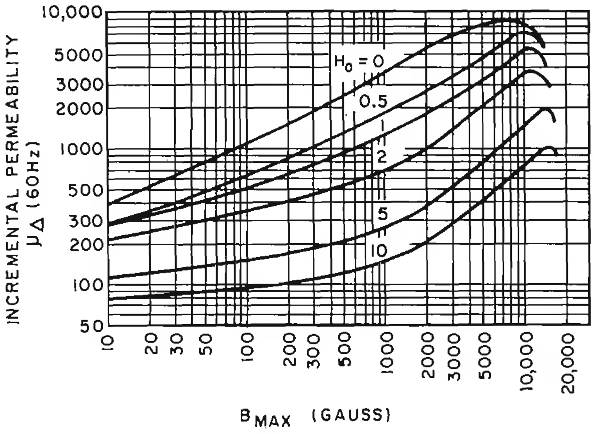


Fig. 1. Incremental permeability curve for AISI grade M-22 laminations where H_0 is the d.c. magnetizing force in core.

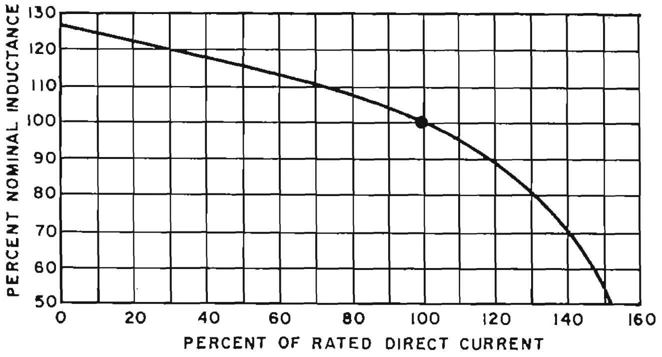


Fig. 2. Effect of d.c. in a typical filter choke. Inductance drops linearly until rated d.c. is flowing through coil, then drops rapidly as core saturates. The linear portion of the curve has less slope for inductors which have larger air gaps.

If a choke is selected for use in a circuit where high a.c. voltages are present across the coil as well as direct current in the winding, it may be checked on an inductance bridge to determine whether it is suitable for the application. With the specified a.c. voltage across the terminals, direct current through the coil is increased from zero to the rated value, observing the inductance. If the inductance remains relatively linear until the rated value of direct current is reached, the choke should be suitable for the application. If inductance drops off before the rated value of d.c. is reached, core saturation is indicated, and the inductor would not be recommended for use in the application.

In order to maintain good regulation and low losses in a filter section, it is important to keep the d.c. resistance of the inductor at the lowest possible value. The largest wire size consistent with the number of turns required and the winding space available is used to accomplish this. The d.c. resistance can be a determining factor in the size of an inductor, as it may be necessary to increase the core size in order to use a large enough wire to maintain the minimum value. Fig. 3 shows the range of inductance and resistance values generally available from standard lamination sizes having a stack height (L) equal to the length of the center leg.

Insulation ratings are often misunderstood because the rated dielectric strength does not directly indicate the maximum voltage which may be continuously applied. To ensure normal life expectancy, the insulation should be rated for at least twice the r.m.s. working voltage plus 1000 volts for commercial applications. Table 1 shows military ratings set forth in MIL-T-27B. The r.m.s. working voltage is defined by EIA Standard RS-197 as "0.707 times the sum of the maximum d.c. voltage and the peak a.c. voltage which may appear between winding and ground under normal conditions of continuous operation." This method may be used to determine the suitability of an inductor for a specific application by working back from the original formula. Subtract 1000 volts from the specified rating and divide the remainder by two. This gives the maximum r.m.s. working voltage which may be continuously applied.

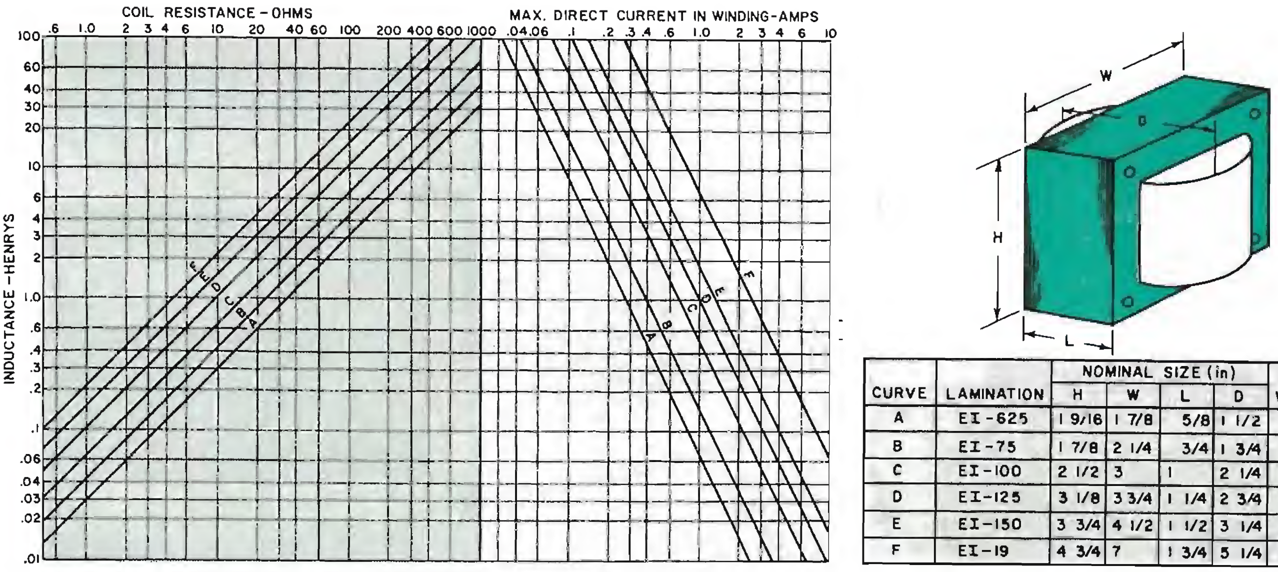
Heating in power inductors is caused by losses in the core and in the coil. Since most power inductors (with the exception of charging reactors) operate at relatively low a.c. flux levels, core loss makes up a small part of the total. The losses due to the resistance of the winding make up most of the total heating. But since the largest wire size possible is normally used to keep d.c. resistance low, the coil or copper losses are seldom large enough to cause excessive heating.

Inductance values are not significantly affected by temperature variations. However, if a choke is to be used at high ambient temperatures, consideration must be given to the type of insulating materials used in construction of the unit. Furthermore, copper losses and d.c. resistances will increase with an increase in temperature so that it may be necessary to use a larger wire size to offset these additional losses.

Construction

General construction of power inductors varies from open-style, varnish-impregnated units for commercial equipment with few environmental requirements to hermetically sealed types built to withstand the most severe temperature and climatic conditions. Basic coil and core construction is similar for all types.

Power inductors characteristically operate at high induction levels. Silicon steel having 3% to 4% silicon content



(A)

CURVE	LAMINATION	NOMINAL SIZE (in)				APPROX. WEIGHT (lb)
		H	W	L	D	
A	EI-625	1 9/16	1 7/8	5/8	1 1/2	1/2
B	EI-75	1 7/8	2 1/4	3/4	1 3/4	1
C	EI-100	2 1/2	3	1	2 1/4	2 1/2
D	EI-125	3 1/8	3 3/4	1 1/4	2 3/4	5
E	EI-150	3 3/4	4 1/2	1 1/2	3 1/4	8
F	EI-19	4 3/4	7	1 3/4	5 1/4	20

(B)

Fig. 3. (A) Typical inductance, resistance, and maximum direct current ratings available with standard-size EI laminations. Assumptions for this chart are: (a) square stack, grain-oriented silicon steel with nominal air gap; (b) maximum current rating is for approximately 50° C temperature rise in open-style unit; (c) maximum number of turns of largest wire size for good design practice; and (d) insulated for 1500-volt dielectric strength. Nominal dimensions for coil and core assembly are shown in (B). For example, it can be seen that the minimum lamination size for a 1.5-henry inductor capable of carrying 1 ampere of direct current would be EI-150. The approximate d.c. resistance is 7 ohms. Dimensions are in part (B).

is widely used for core material because it has a high saturation point and moderate permeabilities. Twenty-four gauge (0.025 inch thick) EI shaped lamination is most common in filter reactors for 60-Hz power supplies, along with 0.019- and 0.014-inch thicknesses. These are normally stacked with a butt stack to provide air gaps. Size and weight can be reduced by using grain-oriented silicon steel material because of the higher induction levels possible. Cost is somewhat higher than standard lamination, but the increased cost is often offset by the savings in size and weight. Because of their low saturation points, higher permeability materials are seldom used in power inductors, except saturable types.

"C" cores are also popular, especially for inductors used in 400-Hz aircraft supplies. Thinner materials are used in these cores, which reduces core losses encountered at these higher frequencies. They are wound with a continuous strip of material, commonly grain-oriented silicon steel, then cut into two C-shaped halves for assembly with the coil. Gaps may be placed between the core halves if desired.

Coils are generally wound in paper-layer construction, with insulating paper between each layer of wire. Bobbin types may be used in some applications, but the paper-layer coil offers better dielectric qualities and is more economical to produce.

As previously mentioned, the largest wire size consistent with winding space available and required number of turns is used in coil construction. In some cases where the wire size requirement exceeds the practical limits of standard wire, copper foil or strips may be used to wind the coil. This is practical only where the inductance value is small, as only one turn per layer is possible.

Insulating materials must be selected to provide the required dielectric strength at maximum operating temperature over the normal life expectancy of the inductor. Besides these characteristics, the material must have sufficient mechanical strength to maintain its insulating properties even after suffering the stresses that are encountered in winding.

Insulating materials are categorized by maximum operating temperature affording normal life expectancy. Both military and commercial specifications list these classes of insulating materials. Although designations for these classes differ for military and commercial classifications, they are similar in temperature characteristics. A listing of both classes is shown in Table 2. Unless otherwise specified, commercial units are normally constructed using class A insulating materials capable of continuous operation at 105°C maximum for normal life expectancy. This corresponds to military class R. The operating temperature includes the ambient temperature surrounding the unit and the allowable temperature rise of the unit.

External packaging is determined to a large extent by the amount of protection required. In military applications, hermetically sealed types are generally preferred, although the encapsulated and molded types are increasing in popularity. In commercial applications, where equipment will be operated under normal room temperatures, open-frame construction is often quite adequate.

Other factors that determine packaging are space available in the equipment, heat dissipation, and, of course, the cost of the item. Open construction offers better heat dissipation and lower cost but is not capable of withstanding severe climatic conditions. The (*Continued on page* 78)

Table 1. Military dielectric strength requirements (MIL-T-27B).

Working Voltage*	R.M.S. Test Voltage
≤25	50
>25 to 50, incl.	100
>50 to 100, incl.	300
>100 to 175, incl.	500
>175 to 700, incl.	2.8 × working voltage
>700	1.4 × working voltage + 1000

*Working voltage is defined by MIL-T-27B as "the maximum instantaneous voltage stress that may appear under normal rated operation across the insulation to be considered." Ref. MIL-T-27B, Table XVI.

Table 2. Temperature classifications of insulating materials.

Military Class	Commercial Class	Maximum Temperature °C	Typical Materials
Q	—	85	Cotton, silk, paper
—	O	90	Cotton, silk, paper
R	A	105	Cellulose acetate, paper
S	B	130	Mylar, glass fabric
V	F	155	Glass fabric
T	—	170	Mica, asbestos, silicon glass
U	—	170+	Mica, glass fabric
—	H	180	Mica, asbestos, silicon glass
—	C	180+	Mica, glass

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hermetically sealed types offer the greatest amount of protection and best appearance, while having the poorest heat dissipation and higher cost. Many types of construction between these two extremes are available which combine the desired qualities of each. For example, many fully enclosed types of inductors are available which are not hermetically sealed but which have more protection and better appearance than the open-frame types.

The hermetically sealed inductor is completely enclosed in a metal case which has been filled with a suitable compound and sealed by soldering all the seams and openings. Filling material may be wax, pitch, epoxy, or polyester, depending upon the temperature requirements of the item. This type offers maximum protection against mechanical and environmental stresses but is generally larger and heavier than equivalent units of other construction. Molded and encapsulated types offer reasonable protection and are increasing in usage where size and weight are significant in equipment design. Epoxies are prominent as encapsulants, and silicon rubber is often used for high-temperature applications. Encapsulated or molded inductors offer good moisture resistance, mechanical strength, and heat dissipation but are not as impervious to thermal conditions as hermetically sealed types.

Open-frame, varnish-impregnated units are quite common in commercial applications where environmental conditions are not severe. Varnish impregnation offers moderate protection against moisture and climate. Variations of this open construction offer several levels of protection by use of end covers, partial enclosures, etc.

Commercial & Military Specs

MIL-T-27B, "Transformers and Inductors (Audio, Power and High Power Pulse), General Specification for," sets forth minimum standards for inductors used in military equipment. Areas covered by this specification include: materials, design, inspection requirements, case sizes, marking, environmental requirements and testing, and packaging levels. Transformers and inductors supplied to this specification are normally hermetically sealed (grades 1 or 4) or encapsulated or molded (grades 2 or 5). Open-frame types may be purchased to this specification (grades 3 and 6) but are normally used only where further protection will be provided in the equipment, such as encapsulation of subassemblies.

Transformers and inductors supplied to MIL-T-27B are marked with a MIL type number, such as TF4RX01EA. This number indicates the grade, temperature class, life expectancy, family, and case size of the unit. An additional three digits following this type number indicate that the unit is designed to a particular government MS drawing.

Compliance with this specification is mandatory for items supplied for most military equipment, and complete qualification testing must be performed for many contracts.

Commercial standards, although not as strictly followed by individual contractors as the military equivalents, set forth specifications which are generally adhered to by the electronics industry. For power inductors, RS-197 (revision of TR-110-B) covers power filter inductors and RS-181 (revision of TR-127) covers iron-core charging inductors. These particular standards are available through the engineering department of the Electronic Industries Association (EIA).

Specifying Power Inductors

The following ten points should be considered when selecting or specifying inductors for electronic power circuits. Some of these points will be dictated by the electrical requirements of the circuit in which the inductor is to be used, while others will depend largely upon the construction of the equipment and its intended usage.

1. Application and circuit used. For charging inductors, a schematic of the circuit should be made available, while for filter inductors, specifying the type of rectifier circuit (*i.e.*, full-wave bridge, etc.) should be adequate.
2. Inductance and tolerance. Due to the complexity of design and number of variables on inductors carrying direct current, at least 10% tolerance should be allowed. Standard tolerance on off-the-shelf inductors of this type is —20% to +50%.
3. A.c. operating voltage and frequency.
4. Direct current or range of direct-current values that are present in the coil.
5. D.c. resistance and tolerance when necessary to circuit operation.
6. Dielectric strength and/or maximum working voltage.
7. Case type (open frame, encapsulated, etc.).
8. Terminals (wire leads, turret type, lugs, etc.).
9. Environmental requirements, including maximum temperature rise and operating temperature, moisture resistance, thermal shock, vibration and shock, life expectancy, and other applicable factors.
10. Applicable military or commercial specifications. ▲