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THE DESIGN OF SATURABLE REACTORS

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A method for the design of a stirred reactor is described. This method consists of plotting from measured values a set of characteristic curves for the reactor to be employed, and of substituting certain properties concerning these curves by additional measurement. If the reactor properties can be substituted to within the accuracy desired, a universal curve can be developed from which design information is obtained.

In the case of certain connected stirred reactors, the design method described was applied. Through the application of this method it is possible to predict the values of effective and peak stirring current for a wide range of the three variables—load, applied stirring current, and maximum power current. The point of maximum power current is obtained and the effect of varying the design indicated quantitatively.

This is an interim report. Work is continuing.

WILLIAM PROCTOR, JR.
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AUTHORIZATION

PROBLEM STATE

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ABSTRACT

A method for the design of saturable reactors is described. This method consists of plotting, from measured values, a set of characteristic curves for the material to be employed, and of substantiating certain properties concerning these curves by additional measurement. If the required properties can be substantiated to within the accuracy desired, a universal curve can be developed from which design information is obtained.

In the case of series-connected saturable reactors with split Hypersil cores, the design method developed was accurate to within about three percent. Through the application of this method it is possible to predict the values of effective and peak alternating current for a wide range of the three variables—load, applied alternating voltage, and control current. The point of maximum power transfer may also be obtained and the effect of varying the design parameters indicated quantitatively.

PROBLEM STATUS

This is an interim report; work is continuing.

AUTHORIZATION

NRL Problem E03-14R
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THE DESIGN OF SATURABLE REACTORS

INTRODUCTION

The principle of the magnetic amplifier¹ has been known for over thirty years but only in the last decade has this principle been utilized to any great extent. About 1930 the magnetic amplification principle was revived in Europe, and, through the application of high-permeability magnetic alloys and improved metallic rectifiers, magnetic amplifiers were developed and have displaced electronic amplifiers in an increasing number of applications. As compared with the electronic amplifier, the magnetic amplifier is characterized by ruggedness and reliability.² It requires no warm-up time since there are no filaments or filament supplies. The input and output are naturally isolated and good zero stability exists. However, the magnetic amplifier has a limited frequency response, thus restricting its application.

The amplification of a magnetic amplifier is obtained through the use of a saturable reactor. It is evident, therefore, that a simple accurate method of designing the saturable reactor is desirable to facilitate the design of magnetic amplifiers. The saturable reactor design methods found in the literature are not, in general, specific but are based on theoretical or empirical analyses of saturable reactor performance, and are thus characterized by the properties of these analyses. In the theoretical analyses the magnetization curves of the core material are usually approximated either by straight lines or by exponential or hyperbolic functions. Based on these approximations, expressions for the dependent variables are derived through straightforward, though generally complex, mathematical manipulations. Notwithstanding the many assumptions made relative to wave shape, load, leakage and other minor factors, the measured values of the dependent variables usually agree with the calculated values for some sample reactor, in these several analyses. The available empirical analyses are less complex than the theoretical but, because of oversimplification, generally afford less accurate expressions for the dependent variables.

The design method described in this report allows simplification without the loss of accuracy; it is based on graphical relations which are determined by measurements for a

¹ Rex, H. B., "Bibliography on Transducers," *Instruments*, Vol. 21, No. 4, April 1948

² A fire-control technician from the German cruiser, "Prinz Eugen" claimed that the panels of the magnetic amplifiers were not opened once during the ten years he was on that ship. From papers presented at the Naval Ordnance Laboratory Magnetic Materials Symposium, NOL R-1091, June 1948.

given core material and type of reactor. The design curves obtained have a universal property, within limits, for a core material, and therefore the range of application is broad. To familiarize the reader with the graphical relations used in this design method, a sample graphical analysis of a saturable reactor is presented.

ANALYSIS

Reactor Characteristic Curves

The saturable reactor to be analyzed here is series-connected and employs split Hypersil cores. The power windings of this reactor have negligible resistance. With the reactor operating in conjunction with a sinusoidal voltage source, the short circuit characteristics are determined by measuring the peak current as a function of the applied voltage for various constant values of control current. If this data is plotted as peak current versus rms supply voltage for various constant control current values, as shown in Figure 1, the resulting curves, describing the short circuit characteristics, are termed the reactor characteristic curves.

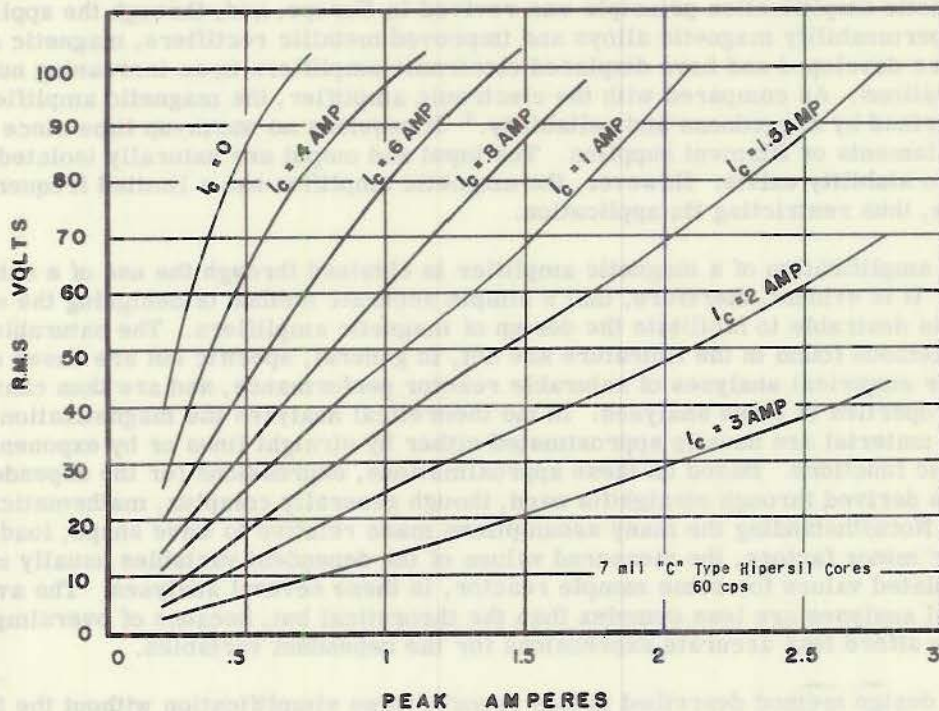


Figure 1 - Reactor characteristic curves

Reactor Operating Loci

If the saturable reactor is connected in series with a load resistance as shown in Figure 2, the operation of the circuit may be described through the application of a reactor operating loci together with the reactor characteristic curves. The circle diagram used to describe a series combination of a fixed resistance and a variable inductance may be applied here if the saturable reactor is assumed to be a linear variable inductance. Thus, if a sinusoidal current is also assumed, the operating loci may be plotted directly on the reactor

characteristic curves as follows: Two points are located, one on the voltage axis corresponding to the supply voltage and a second on the peak current axis corresponding to the peak current which would result if the reactor impedance were zero, and a quadrant of an ellipse is constructed using these values for the semi-major and semi-minor axis as shown in Figure 3.

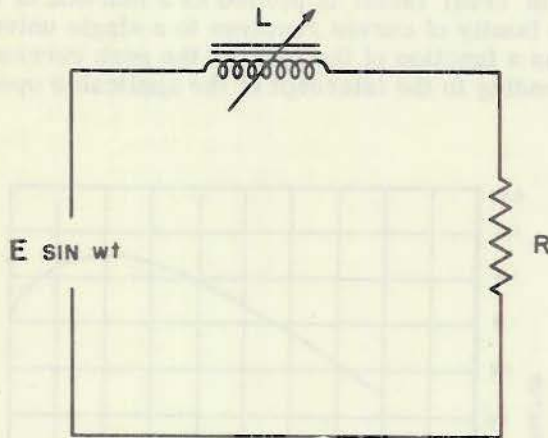


Figure 2 - R-L series circuit

The theoretical value of the peak current flowing in this circuit, for any particular value of control current, may be determined from the intersection of this loci with the appropriate control current curve. Helber³ has shown that, notwithstanding the actual high harmonic content of the current wave, the peak currents indicated by this operating loci correspond closely to the measured values of peak currents. Two facts should be noted with regard to the use of these curves: (1) the ordinate value of voltage corresponding to a point on the operating loci does not, in general, represent the voltage appearing across the reactor. (2) because of the variable harmonic content of the current wave, the rms value of current is not related to the peak value of current by a fixed ratio; i.e., the crest factor (the ratio of peak to rms current) is a variable.

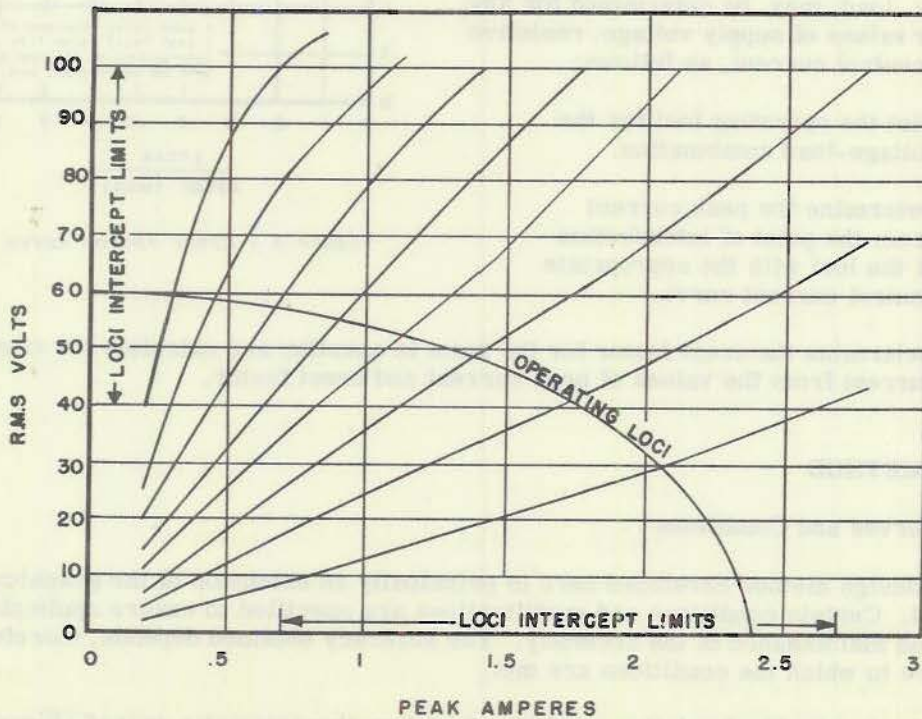


Figure 3 - Construction and limits of operating loci

³ Helber, Carl, "Designing Saturable Core Reactors for Specific Uses," *Electronic Industries and E.I.*, Dec. 1947

Crest Factor Curves

In an effort to establish the rms current for any values of supply voltage, control current, and resistive load, the values of rms current were measured for points on several different operating loci. The crest factor was taken as the ratio of the peak current corresponding to the ordinate value of the point in question to the measured value of rms current for the same point. It was found that if this crest factor is plotted as a function of the peak current a family of curves results. This family of curves resolves to a single universal curve (Figure 4) if the crest factor is plotted as a function of the ratio of the peak current at any point to the value of peak current corresponding to the intercept of the applicable operating loci on the peak current axis.

The accuracy with which the operating loci and the crest factor curve may be applied to determining the rms current depends upon the relative location of the operating loci. The limits within which the loci must fall are established on the basis of the accuracy desired and are determined by measurement. If the extremities of the axis of the elliptical operating loci fall within the limits shown in Figure 3 the accuracy obtained for the subject reactors is within about three percent. Within this operating range (the range of applicability of the operating loci) the rms current in a load may be determined for any particular values of supply voltage, resistive load and control current, as follows:

1. Plot the operating loci for the voltage-load combination.
2. Determine the peak current from the point of intersection of the loci with the appropriate control current curve.
3. Determine the crest factor for the point in question and calculate the rms current from the values of peak current and crest factor.

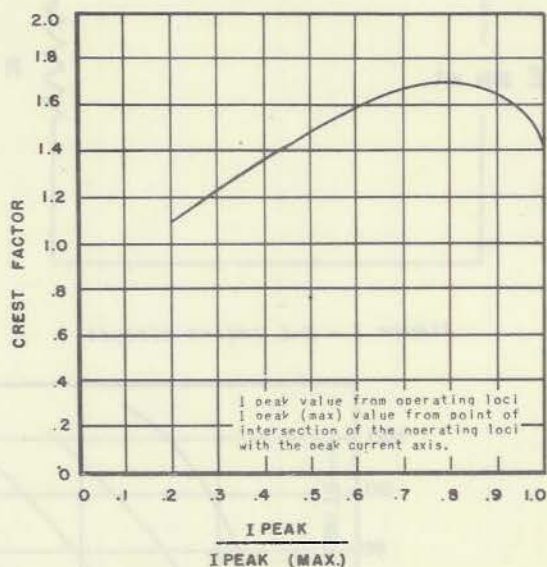


Figure 4 - Crest factor curve

DESIGN METHOD

Design Curves and Conditions

The design method developed here is principally an extension of the graphical analysis presented. Certain conditions and modifications are specified to ensure applicability of the curves and maintenance of the accuracy. The accuracy obtained depends, therefore, upon the degree to which the conditions are met.

The basic graphical relation used is a "reactor characteristic curve" (Figure 5) plotting rms volts per turn per square inch versus peak ampere turns per inch for various constant values of control ampere turns per inch (H_{DC}). Data for this curve is obtained from a test reactor which employs the material to be used in the designs. To ensure applicability

of these curves it is specified that in any reactor to be designed or rated with these curves the relative values of air gap length and leakage shall be approximately equal to the relative values of these parameters in the test reactor employed in their attainment.

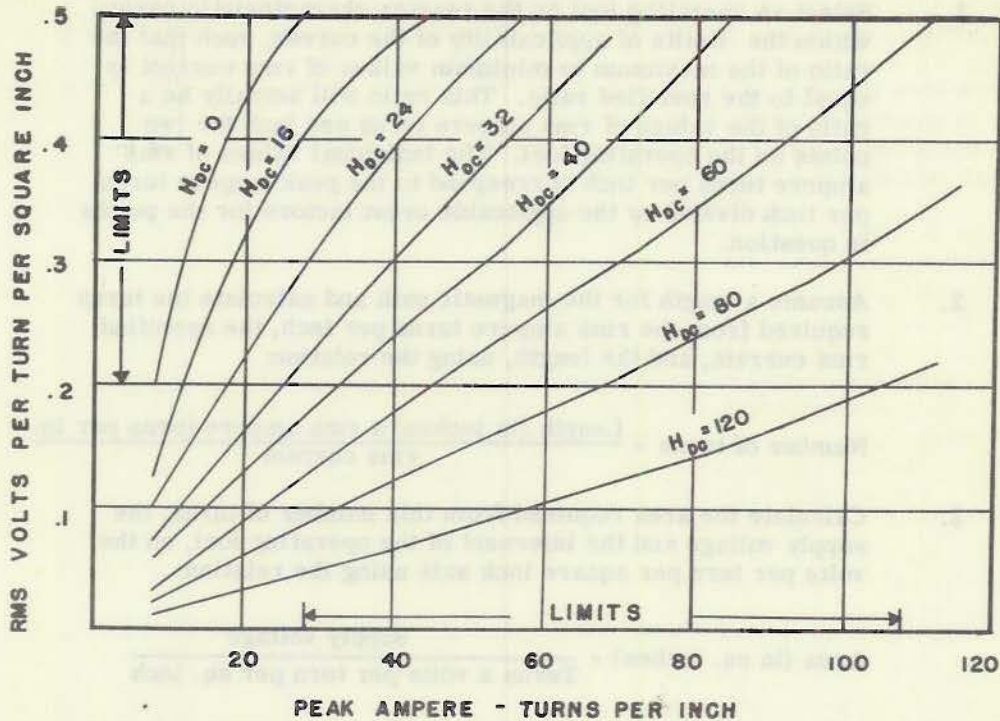


Figure 5 - Characteristic design curves

Since the elliptical operating loci employed in this design method is related to an assumption of a pure inductance and a series resistance, it is also specified that the load shall be resistive for the applications of this design method and that the resistance of the output windings of any reactor to be designed or rated shall be either negligible or combined with the load for calculations. The resistance of the output windings of the test reactor used in the establishment of a set of design curves, accordingly, should be negligible. The limits within which the operating loci must fall are established on the basis of the accuracy desired and are determined by measurement.

A crest factor curve as described is also used in this design method for the purpose of determining the rms current from the peak current for any point in the operating range. The data for this curve is obtained from the test reactor operating on a number of loci representative of the conditions within the operating range. The applicability of this curve is dependent on two further conditions: The alternating supply voltage shall be sinusoidal, and the frequency shall be constant for the application and attainment of the curves.

Design Procedure

The design of a saturable reactor is carried out through a straightforward application of the design curves, but the procedure will vary depending upon the specifications to be fulfilled. If it is assumed, for example, that a saturable reactor is to be designed to control the

power supplied to a load—where the maximum and minimum values of rms load current, the supply voltage, the resistance of the load, and the control voltage and power are specified—the procedure would be as follows:

1. Select an operating loci on the reactor characteristic curves within the limits of applicability of the curves, such that the ratio of the maximum to minimum values of rms current is equal to the specified ratio. This ratio will actually be a ratio of the values of rms ampere turns per inch for two points on the operating loci. The individual values of rms ampere turns per inch correspond to the peak ampere turns per inch divided by the applicable crest factors for the points in question.
2. Assume a length for the magnetic path and calculate the turns required from the rms ampere turns per inch, the specified rms current, and the length, using the relation:

$$\text{Number of turns} = \frac{\text{Length (in inches)} \times \text{rms ampere turns per in.}}{\text{rms current}}$$

3. Calculate the area required from this number of turns, the supply voltage and the intersect of the operating loci, on the volts per turn per square inch axis using the relation:

$$\text{Area (in sq. inches)} = \frac{\text{Supply voltage}}{\text{Turns} \times \text{volts per turn per sq. inch}}$$

4. Calculate the control turns and wire size for control and output windings.
5. Calculate the window area required and compare with the window area available.
6. Repeat steps 2, 3, 4, and 5 until the required design is determined.

The qualitative effect of varying the various design parameters should be understood before the design of a saturable reactor is undertaken since, for any particular design, consideration of these relations will aid in the selection of the operating loci, core dimensions and turns. For a given saturable reactor the effect of increasing the supply voltage is to expand the operating loci uniformly about the origin. An increase of load resistance causes the "current" intercept of the operating loci to move toward the origin. Increasing the number of turns of the power winding causes a point on the "voltage" axis to correspond to a higher voltage and a point on the "current" axis to correspond to a lower current. Increasing the area of the magnetic path also has the effect of increasing the voltage corresponding to a point on the "voltage" axis, whereas increasing the length of the magnetic path has the effect of increasing the current corresponding to a point on the "current" axis. The quantitative effect of varying these design parameters may be determined without difficulty since the relations described are all proportionalities.

The ratio of iron, copper, or total weight to the output power may be calculated from the data presented in the design curves. Other factors may also be determined including (a) the relationship between the applied voltage and the ratio of maximum to minimum power (corresponding to the maximum and minimum control) for a given load, (b) the relationship between the load and this power ratio for a given voltage, and (c) the optimum values of control current for a given voltage-load combination.

The design method described above has been used successfully to design both series- and parallel-connected saturable reactors with split Hypersil cores. Lamination sizes of three, seven and fourteen mils were used. To maintain the high degree of accuracy indicated, it was found that a set of reactor characteristic curves and a crest factor curve should be obtained for each type of reactor and lamination thickness.

CONCLUSIONS

The design method described in this report is simple to carry out and provides a degree of accuracy which is sufficient for many applications. If a higher degree of accuracy is required, additional design curves may be obtained wherein the limits of application and the specified conditions are more stringent.

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