6-3-1958

A Study of the Reset Cycle of a Half-Wave Self-Saturable Magnetic Amplifier

William W. Lee

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MAGNETIC AMPLIFIER · LEE

This thesis by ....William W. Lee, Jr.................
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NAME AND ADDRESS	DATE

A STUDY OF THE RESET CYCLE OF A HALF-WAVE SELF-SATURABLE MAGNETIC AMPLIFIER

A Thesis
Presented to
the Faculty of the Department of Electrical Engineering
University of New Mexico

In Partial Fulfillment
of the Requirements for the Degree
Master of Electrical Engineering

by
William W. Lee, Jr.
June 1958

This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

E F Castetter
DEAN

DATE June 3, 1958

Thesis committee

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ACKNOWLEDGMENTS

This thesis was written while on active duty with the U. S. Navy, stationed in a rural community. Library and laboratory facilities necessary for the completion of this work were available only through the co-operation of many individuals.

Particular appreciation is expressed to Mr. Leslie M. Gower of the University of Tennessee for his assistance in locating reference material, and to Mr. James R. Holpp and Mr. J. L. Coursey for making available probably the only suitable laboratory facilities within seventy five miles.

Gratitude is also expressed to the Arnold Engineering Company, Marengo, Illinois, for furnishing the Deltamax core used in the experimental phase of the investigation.

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THE PROBLEM AND DEFINITION OF TERMS

The student of the magnetic amplifier has at his disposal a bewildering array of literature on the subject. Up to 1951, two comprehensive bibliographies had appeared on magnetic amplifiers and related devices and much has been published since that time.[1, 2] Although patented in its basic form in 1919,[3] the self-saturable circuit appears not to have been widely understood or used until World War II, after which time many articles proposing theories of operation appeared. These articles, while yielding useful results which are, for the most part, confirmed by experimental data, neglect entirely or touch lightly on the operation of the circuit during the reset cycle.

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CHAPTER I

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The student of the magnetic amplifier has at his disposal a bewildering array of literature on the subject. Up to 1951, two comprehensive bibliographies had appeared on magnetic amplifiers and related devices and much has been published since that time.[1, 2] Although patented in its basic form in 1919,[3] the self-saturating circuit seems not to have been widely understood or used until World War II, after which time many articles propounding theories of operation appeared. These articles, while yielding useful results which are, for the most part, confirmed by experimental data, neglect entirely or touch lightly on the operation of the circuit during the reset cycle.

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I. DEFINITION OF TERMS USED

Constant current reset. A method whereby the flux is reset to some predetermined value by means of a known current function acting on the core through its windings.

Constant voltage reset. A method whereby the flux is reset to some predetermined value by means of a known voltage function applied across its windings.

Control winding. The winding of a magnetic amplifier employed to control the power delivered to the load.

Firing angle. The angle of the power supply frequency at which the core saturates, applying the full power supply voltage across the load.

Gating cycle. The half of the power supply cycle during which useful power is delivered to the load.

Gate winding. The winding of a magnetic amplifier through which the load current flows.

Magnetic amplifier. An electromagnetic device employing the principle of saturation whereby power delivered to a load may be controlled by a smaller amount of power applied to the amplifier.

Reset cycle. That portion of the power supply cycle

during which the flux is reset to a desired value. No useful load current is delivered by the core undergoing reset.

Reset function. The voltage appearing across the gate winding during the reset cycle.

Self-saturation. A phenomenon in magnetic amplifiers whereby the supply voltage is prevented by a rectifier in the gate winding from acting on the core during the reset cycle.

Transfer function. A performance plot of an amplifier whereby some property of its output is plotted as a function of some property of its input.

II. THE PROBLEM

Statement of the problem. It was the purpose of this study (1) to investigate the reset cycle of a half-wave self-saturable magnetic amplifier by graphical analysis of the irregular voltage functions appearing across the gate winding during reset; and (2) to determine if possible from this analysis a more satisfactory design method than those now available. Conditions of constant current reset were employed and the core material used had a nearly rectangular hysteresis loop. Resistive loads only are considered.

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Significance of the study. It is the opinion hysteresis loop of the core material forms a basis for magnetic amplifier design has been established by many investigators. These hysteresis loops are affected by many factors, among them core material, size, physical configuration, power supply frequency, nature of the load impedance and other external circuitry. The application of these functions to approximate transfer characteristics has been widely discussed, and in fact appears to be the only link presently used to relate average output to dc input. Certain difficulties arise when attempting to use the hysteresis loop for this purpose. Obtaining the hysteresis loop may in itself be a problem. At least one core material manufacturer[4] has published detailed hysteresis loops for his products for direct current, sixty cycles and four hundred cycles. Admittedly these appear to be the most used power supply frequencies in this country. However power supply systems delivering fifty cycles are common in Europe, while other frequencies from 25 to 100 cycles are found.[5] There is nothing, of course, to preclude the application of

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[4] The Arnold Engineering Company, Marengo, Illinois, Bulletin TC-101A, Properties of Deltamax, 4-79 Mo-Permalloy, Supermalloy, March 15, 1953, reprinted January, 1956.

[5] World Electrical Current Characteristics, United States Department of Commerce, Washington 25, District of Columbia, October 1948, cited in Reference Data for Radio Engineers, third edition, Federal Telephone and Radio Corporation, New York, March 1950, p. 553.

frequencies in the range of 400 cycles upward where the resulting saving in weight justifies such action, as in aircraft equipment. If a hysteresis loop is not available for the frequency desired, it would be necessary to plot one, requiring special equipment and techniques.

Having obtained a hysteresis loop, the problem is only partially solved. Neither the static nor the dynamic loop represents the transfer characteristic. It is some function lying between them.[6]

Therefore, a method of determining the transfer characteristic independently of the supply frequency is desirable, even though it answers only one question, namely ''How many control ampere-turns for cutoff?''

III. ORGANIZATION OF THE THESIS

The remainder of the thesis is divided into chapters as follows:

Chapter II - Review Of The Literature. Articles from the technical literature relating to the problem at hand were reviewed. Particular attention was given to those discussions dealing with the self-saturable circuit, properties and testing of magnetic material, and the reset cycle. A section on the historical development of the magnetic

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[6] Cf. post, p. [illegible].

amplifier was included.

Chapter III - Method. The line of attack used on the problem, the methods used to obtain data, and descriptions of special equipment employed were discussed in detail, along with assumptions used with justifications for them when applicable.

Chapter IV - Data. The data taken in the study is presented in this chapter.

Chapter V - Conclusions. The results of the study are revealed and their significance discussed.

CHAPTER II

REVIEW OF THE LITERATURE

A complete review of the literature devoted to the general subject of magnetic amplifiers would in itself be a major undertaking. Literally thousands of papers have been published in this country and abroad on the subject, to say nothing of the patents issued covering magnetic amplifier devices. Therefore, this review will be limited to three general areas which have bearing on the thesis topic. First, a general review of the historical progress of the magnetic amplifier and saturable reactor art is presented. Second, several papers which are widely referred to by other investigators on the general subject of self-saturable magnetic amplifiers are discussed, and finally those few articles dealing directly with the problem of the thesis are reviewed. This latter group includes material on the behavior and testing of magnetic amplifier materials.

Historical development. As was previously stated, the technical literature of the twentieth century contains a wealth of information on magnetic amplifiers and related devices. The bibliographies of Rex and Miles revealed thousands of articles on these devices.[1, 2] Many publications, especially those of the American Institute of

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Electrical Engineers, have presented valuable articles on these devices between 1949 and the present time.

The first practical application of a magnetic amplifier device appears to have been the saturable reactor patented by Frankenfeld and Burgess in 1903.[3] Their disclosure revealed several methods whereby the control circuit could be decoupled from the load winding, but makes no claim regarding the amplifying properties probably inherent in the device. Its principal application appears to have been the smooth control of theatre lighting.

At about the same time, the instrument transformer property of saturable core reactors was recognized by Ryan and embodied in a device whereby direct currents in the range 100-1000 amperes could be measured to an accuracy of ±0.5 per cent by a nulling process.[4]

The first device recognizable as a modern self-saturable magnetic amplifier was patented by J. Jonas in

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[4] H. J. Ryan, ''The Transformer for Measuring Large Direct Currents,'' AIEE Transactions, 20:169-183, 1901.

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[1] H. F. Storm, "[illegible] of Saturable Reactors, Magnetic Amplifiers, etc.," [illegible], [illegible], April, 1948.

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[4] H. J. [illegible], "The [illegible] Direct Currents," AIEE Transactions, [illegible], 1911.

1919 and was used to control the output of metal vapor rectifiers.[5]

Kramer's developments in the field of electrical measurements spurred a great deal of interest in Europe and resulted in many practical applications not only in instrumentation but also in the field of military usage.[6] That a considerable degree of success was achieved in this latter endeavor is evidenced by the fact that the magnetic amplifier fire control equipment installed on the German Cruiser Prinz Eugen required practically no maintenance.[7, 8]

Among other German writers who contributed to the field of knowledge on magnetic amplifiers, Buchhold appears to be the first to relate the amplification of the device

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[5] J. Jonas, ''Apparatus for Regulating the Voltage of Metal Vapor Rectifier Installations,'' United States Patent 1,434,346, issued 4 October, 1920.

[6] W. Kramer, ''A Simple Direct-Current Type of Instrument Transformer Having Real Current-Transformer Properties,'' Elektrotechnische Zeitschrift, 58:1308-1313, 1937, Berlin.

[7] A. O. Black, ''The Effect of Core Material on Magnetic Amplifier Design,'' Proceedings of the National Electronics Conference, 4:427, April, 1948.

[8] The material in footnotes 3 through 7 was cited by W. A. Geyger, Magnetic Amplifier Circuits (New York: McGraw-Hill Book Company, Incorporated), second edition, 1957, pp. 6-21.

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to the properties of the magnetic material.[9]

Literature devoted to the self-saturable circuit. Among the first to describe the property of self-saturation was Dornhoefer.[10] His was the earliest work uncovered that treated the self-saturable circuit as a separate principle. Previous writers described this configuration as an extension of the theory of applying positive feedback by means of additional windings carrying load current.

He summarizes circuit operation in these words:

> The anode winding is capable of developing a large electromotive force due to magnetic flux changes with small values of anode current. . . . Consequently, from t = 0, when the supply voltage becomes positive with positive slope, until some later time all of the supply voltage appears across the anode winding of the reactor, which may be thought of as absorbing a voltage-time integral. The absorbtion of a voltage-time integral by the reactor must be associated with a change of magnetic flux in the reactor core. When the change of flux from the initial value is such that the magnetic flux density reaches a certain critical value, firing occurs. At firing, the reactor no longer can readily change its flux linkages, and the current increases abruptly from a small value to a value sufficient so that the iR drop is approximately equal to the supply voltage.[11]

Dornhoefer derives a relation showing the dependence

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[9] Th. Buchhold, ''On the Theory of the Magnetic Amplifier,'' Archiv fur Elektrotechnik, 37:197-211, 1943 Berlin, cited by N. R. Castellini, ''The Magnetic Amplifier,'' Proceedings of the IRE, February, 1950, p. 151.

[10] W. J. Dornhoefer, ''Self-Saturation in Magnetic Amplifiers,'' AIEE Transactions, 68:835-850, Part II, 1949.

[11] Ibid., p. 837.

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of average output voltage on the flux present in the core at the start of the gating cycle.[12] In order to predict the transfer function of the magnetic amplifier, he attempts to relate the initial flux to a corresponding control magnetizing force by using the upper branch of the dynamic hysteresis loop.[12] Rather poor corelation was obtained between this predicted transfer characteristic and the transfer characteristic observed experimentally. Dornhoefer attributed this discrepancy to the finite radial depth of the core, and felt that eddy current considerations could be neglected.[12] Later writers do not concur in this last assumption.[13], [14]

In 1953, Storm published an analysis of the full wave circuit with low control circuit impedance, assuming a rectangular hysteresis loop.[15] In this, a complete transfer characteristic is proposed which includes both modes of firing, and takes into account the effect of the exciting current on the output. The effect of reverse current flow through the rectifiers is discussed and a relationship

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[12] *Ibid.*, p. 845.

[13] *Cf*. *post*, p. 12.

[14] *Cf*. *post*, p. 21.

[15] H. F. Storm, ''Theory of Magnetic Amplifiers with Square Loop Core Materials,'' *Communication and Electronics*, 9:629-640, 1953.

showing the deterioration of gain that results is derived. In a discussion on this analysis, Lord observes that better corelation between analysis and observed transfer functions occurs for the case of core material with a very rectangular hysteresis loop when the theoretical top of the transfer characteristic is displaced to the left by an amount equal to one-half the static coercive force.[16] In reply, Storm states that the transfer characteristic may be approximated by the major hysteresis loop as modified by a 'shearing factor' whose magnitude is dependent on the width of the static loop, the inductance of the core during saturation and rectifier leakage.

Lehmann used an entirely experimental approach to the problem of determining the transfer characteristic.[17] He states:

> ...The B_0 - H_0 relationship ... is neither the d-c nor the a-c major hysteresis loop, but lies somewhere between these two curves. This relationship can be obtained only by actually plotting the locus of the bottom tips of the minor hysteresis loops over which the core operates .... This curve must be obtained at the actual frequency of operation of the amplifier. At any other frequency the eddy current effects will be different and the minor hysteresis loops obtained will not be those over which the core will actually operate.

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[16] *Ibid.*, p. 637.

[17] Henry Lehmann, ''Predetermination of Control Characteristics of Half-Wave Self-Saturated Magnetic Amplifiers,'' *AIEE Transactions*, 70:2097-2103, Part II, 1951.

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Many papers appear in the literature describing applications in which the half-wave circuit may be used because of its unique properties or its reliability. Early writers point out the greatest disadvantage of the magnetic amplifier as its relatively slow time response. However, Lufcy, Schmid and Barnhard recognized that the response time of the half-wave circuit is never more than one cycle of the power supply frequency.[18] They reason that the time delay is due to the high inductance of the control winding. In the half-wave circuit, the control current is derived from a high resistance source, and during saturation, the inductance of the control winding is negligible, allowing the control current to reach its proper value in a short time. They then propose a servo amplifier such that all control windings that saturate simultaneously are connected in series.

A use of magnetic amplifiers in industrial metering applications is pointed out by Downing.[19] He describes an installation where magnetic amplifiers are employed in measuring and totalizing for measuring the large currents

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[18] C. W. Lufcy, A. E. Schmid and P. W. Barnhard, ''An Improved Magnetic Servo Amplifier,'' Communication and Electronics, 2:281-289, 1952.

[19] E. A. Downing, ''Magnetic Amplifiers in Metering Direct Current on Electrolytic Cell Lines,'' Applications and Industry, 12:93-96, May, 1954.

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flowing in electrolytic cells. The magnetic amplifiers save the great expense involved in the installation of a very large totalizing shunt. An additional advantage claimed is the saving of the 8000 KWH dissipated by such a shunt annually.

The theoretical papers previously discussed deal primarily with the transfer function as based on events taking place during the gating cycle.[20, 21] It was recognized that the average output current is related to the flux present in the core at the beginning of the gating cycle, but no light was shed on the mechanism whereby this initial flux was determined. It was shown only that this value of flux was related to the control current and hence the control magnetizing force by some function lying between the static and dynamic loops of the core material. It was further established that even if the magnetic properties of the core material could be precisely known the exact locus of this transfer characteristic was quite sensitive to rectifier leakage, permeability during saturation and other factors which might be difficult to ascertain.

The above problems may have been the motivation for

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[20] Dornhoefer, op. cit.

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Ramey's investigations.[22] In a report for the Naval Research Laboratory in 1951, he reasoned that (1) if the firing angle remains constant and (2) if the flux goes from some initial value to saturation during the gating cycle then (3) it must return to the same initial value during the reset cycle. In terms of circuit voltages, the area under the volt-time function generated by the core proceeding to saturation from some initial value will be equal but opposite in sign to that generated by flux changing from saturation to the same initial value. He then developed a circuit whereby the flux was reset by applying a sine wave of variable amplitude to the control winding during the reset interval. Several advantages accrued as a result. First, the reset was completed in one-half cycle, second the output was substantially linear over the entire control range and third the output current was substantially the same for variations in input voltage. Variations, improvements

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[22] R. A. Ramey, ''On the Mechanics of Magnetic Amplifier Operation,'' Naval Research Laboratory Report Number 3799, United States Department of Commerce, Washington 25, District of Columbia, January 22, 1951.

and modifications have appeared on Ramey's circuit.[23], [24], [25]

Properties and testing of magnetic materials. That the properties of the magnetic material used in a magnetic amplifier play an important part in its design has been established. The physical construction of the core plays an equally important part in amplifier performance. The following information on the subject is quoted from a manufacturer's bulletin.[26]

> To take full advantage of the high permeability of Deltamax, a gapless type of core construction is suggested. It is well known that with a magnetic material having a maximum permeability of 100,000, an effective air gap of as little as 0.001 inch in the path of a circuit would reduce the effective working permeability to about 4700, if the ratio of air gap to mean length of magnetic path is 0.0002. If the air gap in this same circuit were reduced to a value of 0.0005 inches the effective working permeability would be increased to a value of about 9000. The gapless construction, therefore, naturally results in maximum effective working permeability and also reduces flux leakage to a minimum.
>
> It has been common practice to use stamped laminations of the gapless type for those applications where 0.005 inch or thicker material may be used, and

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[23] C. B. House, ''Flux Preset High Speed Magnetic Amplifiers,'' Communication and Electronics, 10:728-735, 1954.

[24] D. G. Scorgie, ''Fast Response with Magnetic Amplifiers,'' Communication and Electronics, 10:741-749, 1954.

[25] R. L. Van Allen, ''A Magnetic Amplifier for Synchros,'' Communication and Electronics, 10:749-757, 1954.

[26] The Arnold Engineering Company, Marengo, Illinois, Bulletin TC-101A, Properties of Deltamax, 4-79 Mo-Permalloy, and Supermalloy, pp. 3-4, 15 March 1953, reprinted 1956.

and modifications have appeared in many circuits.[23, 24, 25]

Properties and testing of magnetic materials. That the properties of the magnetic material used in a magnetic amplifier play an important part in the design has been established. The physical construction of the core plays an equally important part in amplifier performance. The following information on the subject is quoted from a manufacturer's bulletin.[26]

> To take full advantage of the high permeability of Deltamax, a gapless type of core construction is suggested. It is well known that with a magnetic material having a maximum permeability of [illegible], an effective air gap of as little as 0.001 inch in the path of a circuit would reduce the effective working permeability to about [illegible] if the mean length of magnetic path is [illegible]. If the air gap in this same circuit were reduced to a value of 0.0005 inches the effective working permeability would be increased to a value of about [illegible]. A gapless construction, therefore, naturally results in maximum effective working permeability and also reduces the leakage to a minimum.
>
> It has been common practice to use stamped laminations of the gapless type for those applications where 0.005 inch or thicker material may be used, and

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[23] C. E. House, "Ultra Fast, High Speed Magnetic Amplifiers," Communication and Electronics, [illegible].

[24] D. G. Scorgie, "Fast Response with Magnetic Amplifiers," Communication and Electronics, [illegible].

[25] R. L. Van Allen, "A Magnetic Amplifier for Synchros," Communication and Electronics, [illegible].

[26] The Arnold Engineering Company, Marengo, Illinois, Bulletin TC-101A, Properties of Deltamax, 4-79 Mo-Permalloy, and Supermalloy, pp. [illegible].

> when the alloy does not exhibit directional properties. However, the stamping, annealing, and handling of thinner laminations becomes troublesome and costly, and is not practical for ultra-thin material. In these latter instances, cores are fabricated by continuously winding thin, insulated strip about a mandrel to produce a toroidal, square, or rectangular shape.... In general, the tape wound cores may be fabricated most readily in the form of a toroid, although square or rectangular shapes may be made. Since Deltamax is strain sensitive, it has been commercial practice to encase toroidal cores of this material in plastic containers to prevent any depreciation of magnetic properties by handling or by subsequent wire winding. . . .
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> Since Deltamax is available only in the form of thin strip, due to the severe cold-reduction necessary to achieve its properties, the tape wound core construction is generally used. This type construction is used also in order to obtain maximum utilization of its directional properties.

According to Mitch, saturation induction, coercive force and hysteresis loop rectangularity are usually the most important core material properties considered in the design of magnetic amplifiers.[27] Of these, saturation induction exhibits the smallest variability being 10-20 percent for most commercial materials. This property appears to be chiefly a function of the chemical composition of the alloy, and is less affected by material processing and heat treatment than other properties of the material. The coercive force varies by a factor of as much as two or three to one for nickel-iron alloys and is quite sensitive

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[27] J. E. Mitch, ''Material Properties and Specification of Magnetic Amplifier Cores,'' paper presented before the Los Angeles Section Meeting, AIEE on January 12, 1956.

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[27] J. E. Hitch, "Interpretation and Specification of Magnetic Amplifier Cores," paper presented before the Los Angeles Section, AIEE, on January 17, 1956.

to heat treatment. Rectangularity of a core material may be judged by several factors, among them being ratio of remanent flux to saturation flux, eddy current considerations, and core geometry. Variation of the ratio of remanent to peak induction is smallest for grain oriented 50 per cent nickel-iron alloys. The maximum differential permeability will vary by a ratio of as high as five to one, being affected by metallurgical processing, final heat treatment, eddy currents, and core geometry. Eddy current losses depend on material thickness, resistivity and maximum rates of change of flux within the core. A toroidal core with a low ratio of cross section area to diameter will have a greater differential permeability as well as a larger ratio of remanent to peak induction.[28]

Although rectangularity is useful in that it provides higher efficiency and facilitates design, it has one drawback worthy of note. Batdorf and Johnson describe an instability noted in magnetic amplifiers using rectangular core material, some times referred to as 'triggering'.[29] While the load current can be reduced smoothly from its maximum value by adjustment of the control current, once

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[28] Discussion by D. C. Dieterly on S. B. Batdorf and W. N. Johnson, ''An Instability of Self-Saturable Magnetic Amplifiers Using Rectangular Loop Core Materials,'' Communication and Electronics, 7:228, 1953.

[29] Ibid., pp. 223-228.

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[29] Ibid., pp. [illegible]-229.

having reached minimum value, the load current cannot be increased again smoothly but jumps suddenly to a rather large value, before the normal transfer characteristic is resumed. They were able to produce this effect on rectangular type materials.

With all of the variables that may be introduced into the magnetic properties of core materials, the need of means of evaluating the characteristics of the final product is apparent. Mitch and others have presented a summary of techniques employed in production testing of tape wound magnetic materials.[30] Two principal methods, the sine flux and sine current methods, are in common use. Their chief difference lies in the source impedance of the exciting current, it being high for sine current and low for sine flux. In both methods, the exciting current is fed through a low resistance shunt to an exciting winding on the core under test. A pickup winding then feeds the induced voltage through an integrator to the vertical plates of an oscilloscope, and the voltage across the shunt (proportional to exciting current, hence magnetizing force) is fed to the horizontal plates. The resulting Lissajous figures represent the hysteresis loop of the

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[30] J. E. Mitch, H. A. Lewis, and R. A. Parnell, ''Production Testing of Tape Core Materials,'' paper presented at AIEE Summer and Pacific General Meeting, Los Angeles, June 21, 1954.

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core under test. The sine flux method is quite sensitive to distortions in the waveforms of the exciting voltage and to stray polarization resulting from rectification of the exciting current occurring in the various circuit contacts. A testing method is proposed which would actually simulate the operation of the core in a half-wave self-saturable circuit. This test consists of determining the average output voltage, or flux change, as a function of the d-c reset magnetizing force for a given value of peak half-wave magnetizing force, plotted for five points on the transfer characteristic. Using the test methods described above, basic core properties can be graded within ranges of 5 to 10 per cent, and the degree of matching obtained by the constant current reset method is comparable with that obtained by other methods.

Problems encountered in the display by oscilloscope of dynamic hysteresis loops are discussed by Lord.[31] Based on an arbitrary criterion of 5 per cent error in indicated values, he derived the following minimum performance characteristics of the amplifiers in the vertical and horizontal deflection circuits. For a three stage amplifier in the horizontal circuit, each stage should have a phase shift of less than 45 degrees at 100th the exciting frequency and at

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[31] H. W. Dorn, "Dynamic Hysteresis Loop Plotting Equipment," Communication and Electronics, 2:482[illegible], 1952.

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Literature devoted to the reset cycle. Although mentioned earlier by other investigators, notably Lehmann, Lord appears to be the first writer to consider in detail the effects of eddy currents on the operating hysteresis loops, and hence on the transfer characteristic of self-saturable magnetic amplifiers.[32], [33] He points out that previous analyses, for reasons of mathematical expediency, chose to represent the B-H function of the core material as having a finite maximum differential permeability. Actual materials are cited whose permeabilities, while finite are quite high, of the order of 10^6. It is further stated that plotted transfer characteristics exhibit slopes far less than that indicated by the maximum differential permeability. His feeling was that some important factor was being over-

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[32] Lehmann, op. cit., p. 2099.

[33] H. W. Lord, ''The Influence of Magnetic Amplifier Circuitry Upon the Operating Hysteresis Loops,'' Communication and Electronics, 10:721-728, 1954.

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[34] Lehmann, op. cit., p. [illegible].

[35] H. W. Lord, "The Influence of Magnetic Amplifier Circuitry Upon the Operating Hysteresis Loops," Communication and Electronics, 10:21-[illegible].

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While Lord discusses a mechanism to account partially for some of the discrepancies between theory and observation, Huhta plotted some of the actual waveforms resulting from a core being reset from saturation by means of a constant

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[35] H. Huhta, ''Flux Resetting Characteristics of Several Magnetic Materials,'' Communication and Electronics, 12:111-114, 1954.

[36] Cf. post, p. 45.

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Summary. The following information applicable to the present study was obtained from the review of the literature. (1) It can be easily shown that the average output of a half-wave magnetic amplifier is a function of the ratio of the flux present in the core at the beginning of the gating cycle to the saturated value;[37] (2) the area under the voltage-time function occurring during the reset cycle is a measure of the initial flux available at the beginning of the next gating cycle;[38] (3) the maximum voltage available for reset at any instant during the reset cycle cannot exceed the supply voltage by an amount greater than the iR and rectifier drops;[39] (4) the magnetizing current flowing during the gating cycle may be neglected when calculating the firing angle;[40] (5) core materials are available in which the saturation flux and the remanent flux are approximately equal.[41]

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[37] Dornhoefer, op. cit., p. 845.

[38] Ramey, op. cit., p. 23.

[39] Huhta, op. cit., p. 114.

[40] Dornhoefer, op. cit., p. 844.

[41] The Arnold Engineering Company, op. cit., p. 6.

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Other results noted are; (6) the function relating control magnetizing force to resulting flux change lies somewhere in between the static and dynamic hysteresis loop of the core material involved;[42], [43] (7) hysteresis loops are affected by a great number of factors;[44] (8) severe requirements must be met by equipment used to measure dynamic hysteresis loops;[45] and (9) when reset from saturation only by the action of a constant magnetizing force, irregular waveforms appear across the gate windings.[46]

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[42] Lehmann, op. cit., p. 2101.

[43] Storm, op. cit., p. 640.

[44] Cf. ante, p. 17 et sqq.

[45] Lord, ''Dynamic Hysteresis Loop Measuring Equipment,'' op. cit., p. 271.

[46] Huhta, op. cit., p. 113.

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[42] Lehmann, *op. cit.*, p. 240.

[43] Storm, *op. cit.*, p. 330.

[44] *Cf. ante*, p. 17 *et seq.*

[45] Lord, "Dynamic Hysteresis Loop Measuring Equipment," *op. cit.*, p. 271.

[46] Hunts, *op. cit.*, p. 213.

CHAPTER III

METHOD AND ASSUMPTIONS

It has been shown in the literature that the firing angle of a magnetic amplifier is dependent on the flux present in the core at the start of the gating cycle,[1] and that a measure of this flux is the time integral of the voltage appearing across a winding of the core during the previous reset cycle.[2] In the half-wave self-saturable circuit, the degree of flux reset obtained is determined by the amount of constant magnetizing force applied to the core via the control winding. The designer of such a circuit is faced with the problem of determining quantitatively the ampere turns of control magnetizing force necessary to achieve the degree of control required. Heretofore, this information was obtained from a hysteresis loop of the core at the frequency desired.[3] Inasmuch as it would be quite unreasonable to expect the manufacturer of core material to

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[1] W. J. Dornhoefer, ''Self-Saturation in Magnetic Amplifiers,'' AIEE Transactions, 68:837, Part II, 1949.

[2] R. A. Ramey, ''On the Mechanics of Magnetic Apmlifier Operation,'' Naval Research Laboratory Report Number 3799, United States Department of Commerce, Washington 25, District of Columbia, January 22, 1951.

[3] Henry Lehmann, ''Predetermination of Control Characteristics of Half-Wave Self-Saturable Magnetic Amplifiers,'' AIEE Transactions, 70:2102, Part II, 1951.

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[3] Henry Lehmann, "Standardization of Control Characteristics of Half-Wave Self-Saturable Magnetic Amplifiers," AIEE Transactions, 70:1032, Part II, 1951.

publish hysteresis loops for every frequency for which a designer may reasonably desire information, the designer must often resort to determining the hysteresis loop for himself. As has been pointed out in the literature,[4] this is a procedure which imposes severe requirements on equipment and requires accurate interpretation of results.

The purpose of this investigation was to determine, by a study of the flux changes during the reset cycle of a half-wave self-saturable magnetic amplifier, if a more flexible design criteria than that presently used could be found.

I. THEORY

Reference to the static hysteresis loop in Figure 1, Page 28 shows that a value of direct current magnetizing force only slightly more negative than the magnetizing force corresponding to the knee in the upper left hand quadrant will cause the flux state of the core to change from positive to negative saturation.[5] A finite time, however is required for this change of state to take place.

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[4] H. W. Lord, ''Dynamic Hysteresis Loop Measuring Equipment,'' <u>Communication</u> <u>and</u> <u>Electronics</u>, 2:269-272, 1952.

[5] Reproduced with permission from The Arnold Engineering Company, Marengo, Illinois, <u>Bulletin</u> <u>TC-101-A</u>, ''Properties of Deltamax, 4-79 Mo Permalloy, and Supermalloy,'' page 10, 15 March 1953, Reprinted January 1956.

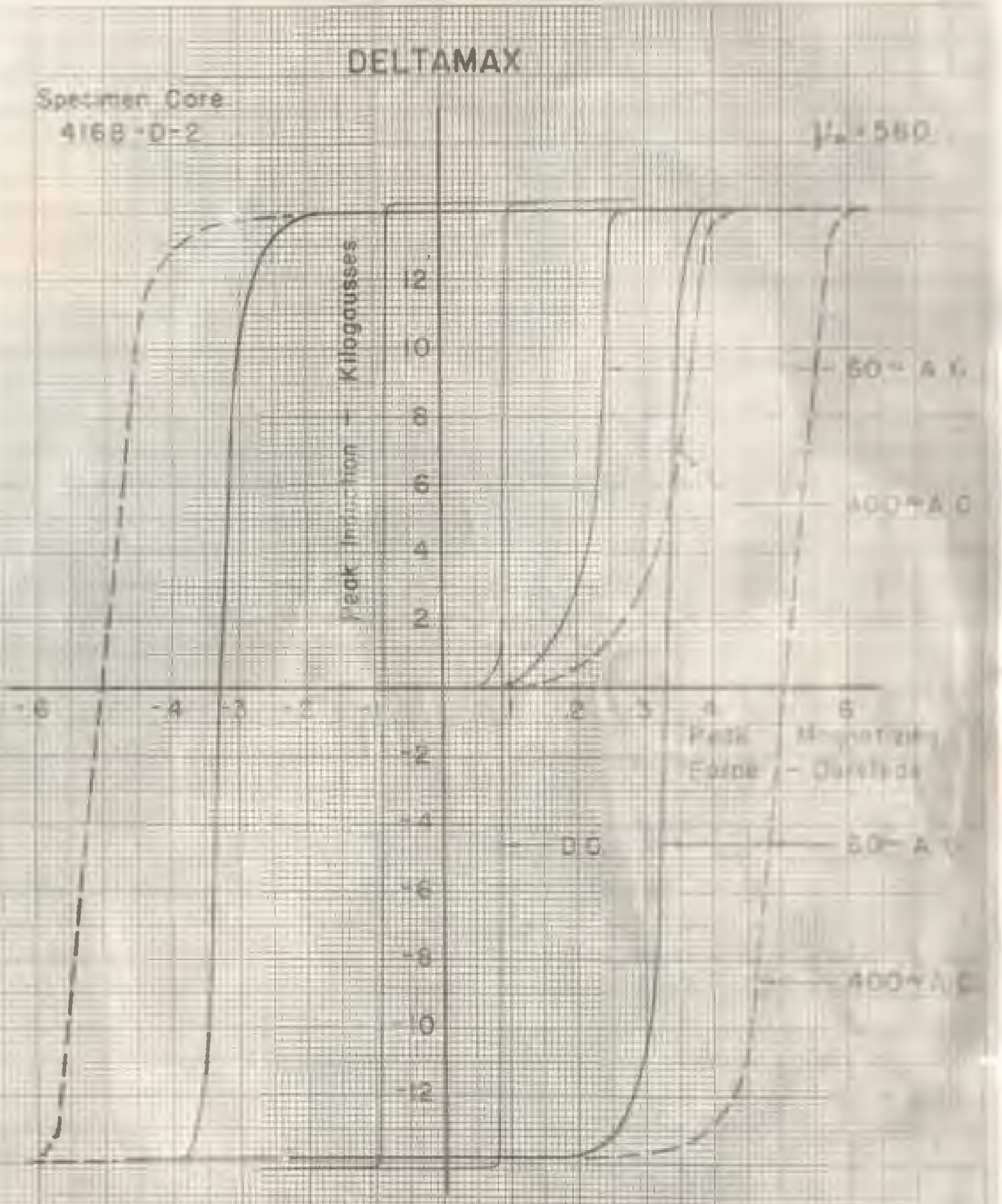

FIG. I D.C. AND A.C. MAGNETIZATION CURVES AND HYSTERESIS LOOPS OF DELTAMAX

In the magnetic amplifier, the flux must be reset to the desired value in a time no greater than one-half cycle of the supply frequency. In order to shorten the time required to produce the desired flux change, additional magnetizing force must be applied.

If sufficient magnetizing force is applied to reset the core to negative saturation in one-half cycle of the supply frequency, the core will not ''fire'' during the succeeding gating cycle, assuming the gate winding is properly designed.

Therefore, a plot showing the relation between control magnetizing force and resulting time required to reset the core from positive to negative saturation might provide the designer of the magnetic amplifier with useful design criteria.

An additional factor, however, must be considered. During the reset cycle the power supply voltage is normally prevented from acting on the core by action of the rectifier. However, if the value of $\frac{d\phi}{dt}$ due to the constant direct current magnetizing force causes a voltage across the gate winding that exceeds the instantaneous supply voltage, the rectifier will conduct. This results in the supply voltage being applied across the gate winding, and the flux changing at a rate determined by the instantaneous value of the supply voltage.

To study these phenomena, the reset functions for a magnetic amplifier were studied both for the case of d-c reset alone, and in the presence of an applied alternating current. In addition, a plot of the reset times for several values of magnetizing force was made.

II. EQUIPMENT USED TO OBTAIN DATA

Magnetic amplifier. The magnetic amplifier was wound on a Deltamax core whose properties are listed in Table I. The properties of the magnetic amplifier are listed in Table II. Much has been written concerning the effects of poor rectifier performance on the behavior of magnetic amplifier circuits.[6] Especially important are the reverse current characteristics. Therefore, particular care was exercised in the selection of the rectifier whose properties are listed in Table III. To emphasize the availability of this device, the manufacturer markets it principally as a replacement for selenium rectifiers in the low voltage power supplies in television sets.[7]

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[6] H. F. Storm, ''Theory of Magnetic Amplifiers with Square-Loop Core Materials,'' Communication and Electronics, 9:636, 1953.

[7] Sarkes-Tarzian Incorporated, Rectifier Division, Bloomington, Indiana, Service Notes #1, ''Replacement Procedure Using Sarkes-Tarzian M-500 Conversion Kit,'' undated.

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[7] Sarkes-Tarzian Incorporated, Rectifier Division, Bloomington, Indiana, Service Notes 2, "Replacement Procedure Using Sarkes-Tarzian M-500 Rectifier Kit," undated.

TABLE I.

PROPERTIES OF CORE USED

Core material	Deltamax
Manufacturers type	5468-D-2
Tape thickness	0.002 inches
Inside diameter	2.500 inches
Outside diameter	3.500 inches
Thickness	1.000 inches
Cross sectional area	0.500 sq. inches
Mean path length of iron	3.000π inches
Saturation flux density	14000 gauss
Stacking factor	0.8
Saturation flux	36,100 lines
Static coercive force	0.09 oersteds

TABLE II.

PROPERTIES OF MAGNETIC AMPLIFIER

Gate winding	505 turns, number 26, AWG
Control winding	540 turns, number 26, AWG
Peak sinusoidal voltage supported by gate winding at sixty cycles	
calculated	69.0 volts
measured	70.9 volts
Control magnetizing force per milliampere control current	
calculated	0.0284 oersteds per milliampere

TABLE III.

PROPERTIES OF RECTIFIER USED

Type	Silicon junction
Manufacturer and type	Sarkes-Tarzian, M-500
Peak inverse voltage (rated)	400 volts
Forward voltage drop (measured)	
at ten milliamperes	0.66 volts
at 100 milliamperes	0.73 volts
Reverse current (measured)	
at ten volts	4 microamperes
at fifty volts	8 microamperes
at 200 volts	20 microamperes

Constant current device. A constant current device was provided by causing the control current to flow through the plate circuit of a type 6AC7 vacuum tube whose bias was varied by a potentiometer in its cathode, and whose screen voltage was stabilized at 150 volts.

Saturating device. To obtain the d-c reset function, the core was saturated in the positive direction by application of a direct current through the gate winding. This current flowed through the plate circuit of a type 6C5 vacuum tube. Provision was made for the sharp cutoff of this plate current by application of approximately 200 volts negative bias to the grid. On application of this bias, a negative trigger pulse was fed to the sweep circuit of an oscilloscope.

Instrumentation. Oscillograms were made with a Tektronix model 535 oscilloscope, whose bandwidth was eight megacycles and whose input impedance exceeded ten megohms, according to manufacturer's specifications. Its deflection sensitivity was calibrated against a Weston model 540 dynamometer voltmeter whose rated accuracy was one half per cent, and found to be twenty-two and two tenths volts per centimeter on the setting used. Current measurements were made with a Sensitive Research Corporation Laboratory standard meter whose rated accuracy was one quarter per cent.

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Instrumentation. Oscillograms were made with a Tektronix model 535 oscilloscope, whose bandwidth was eight megacycles and whose input impedance exceeded ten megohms, according to manufacturer's specification. Its deflection sensitivity was calibrated against a Weston model 340 dynamometer voltmeter whose rated accuracy was one half per cent, and found to be twenty-two and two-tenths volts per centimeter on the setting used. Current measurements were made with a Sensitive Research Corporation laboratory standard meter whose rated accuracy was one quarter per cent.

III. METHOD OF OBTAINING DATA

Magnetic amplifier waveforms. Magnetic amplifier waveforms were plotted using the circuit shown in Figure 2, page 35. The oscilloscope was connected to read the voltage across the gate winding during one entire cycle of the sixty cycle line voltage, with the triggering supplied by the line voltage. Waveforms were taken with values of control magnetizing force corresponding approximately to firing angles of forty-five, ninety, one hundred thirty-five and one hundred eighty degrees.

Reset functions. Constant current reset functions were obtained with the device shown in Figure 3, page 36. The current through the gate winding was adjusted to a value that would produce a magnetizing force of approximately one oersted, sufficient for saturation, so polarized as to oppose the control magnetizing force. With the control current adjusted to the value for which data was desired, approximately two hundred volts negative bias was applied through a toggle switch between the grid and cathode of the 6C5, cutting off the gate winding current. This drop in voltage was differentiated and used to trigger the sweep on the oscilloscope. Two sets of data were thus obtained. The first was obtained to record photographically the actual reset waveform associated with each of the values of

III. METHOD OF OBTAINING DATA

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Reset functions. Constant current reset functions were obtained with the circuit shown in Figure 3, page 33. The current through the gate winding was adjusted to a value that would produce a magnetizing force of approximately one oersted, sufficient for saturation, so polarized as to oppose the control magnetizing force. With the control current adjusted to the value at which data was desired, approximately two hundred volts negative bias was applied through a toggle switch between the grid and cathode of the 605, cutting off the gate winding current. This drop in voltage was differentiated and used to trigger the sweep on the oscilloscope. Two sets of data were taken at a time. The first was obtained to record photographically the actual reset waveform associated with each of the values of

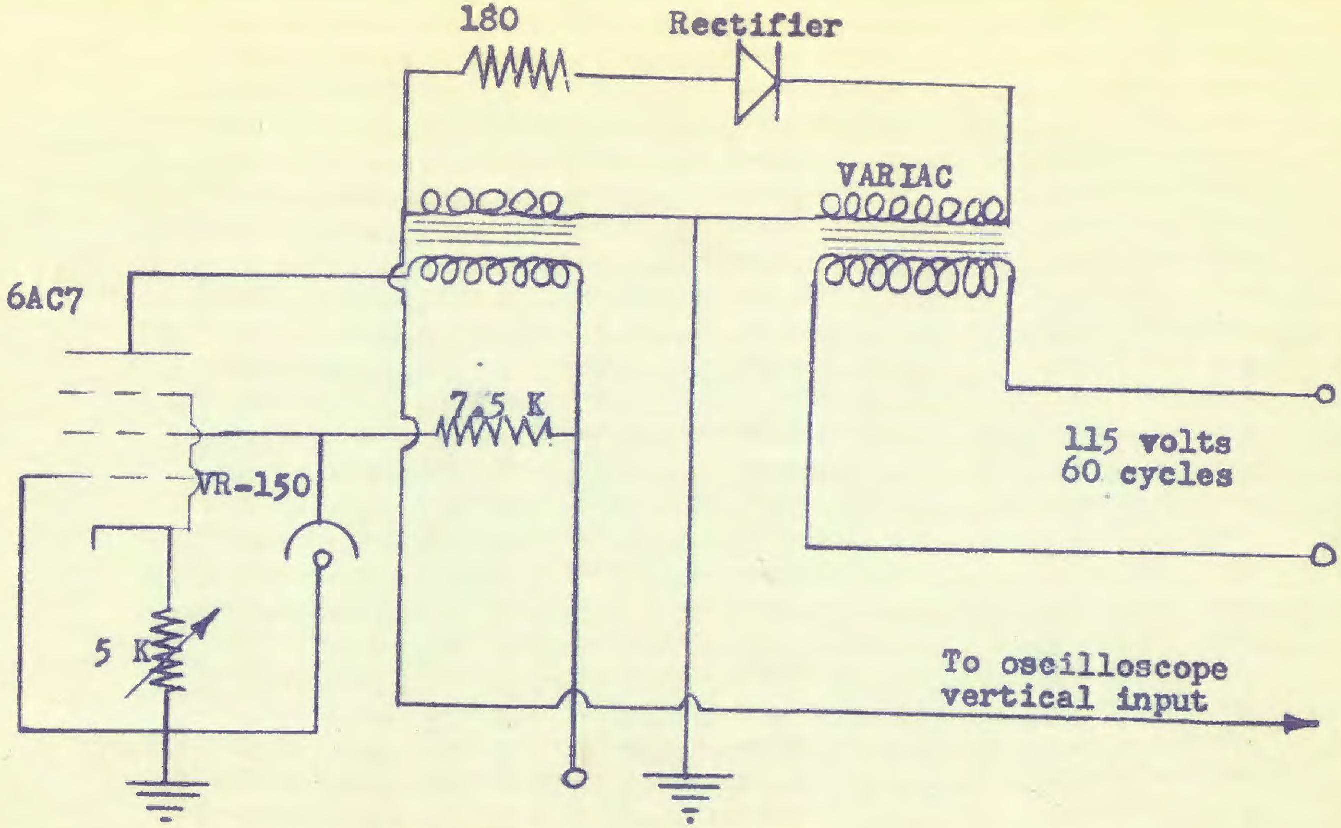

FIGURE 2

CIRCUIT USED TO DETERMINE
MAGNETIC AMPLIFIER WAVEFORMS

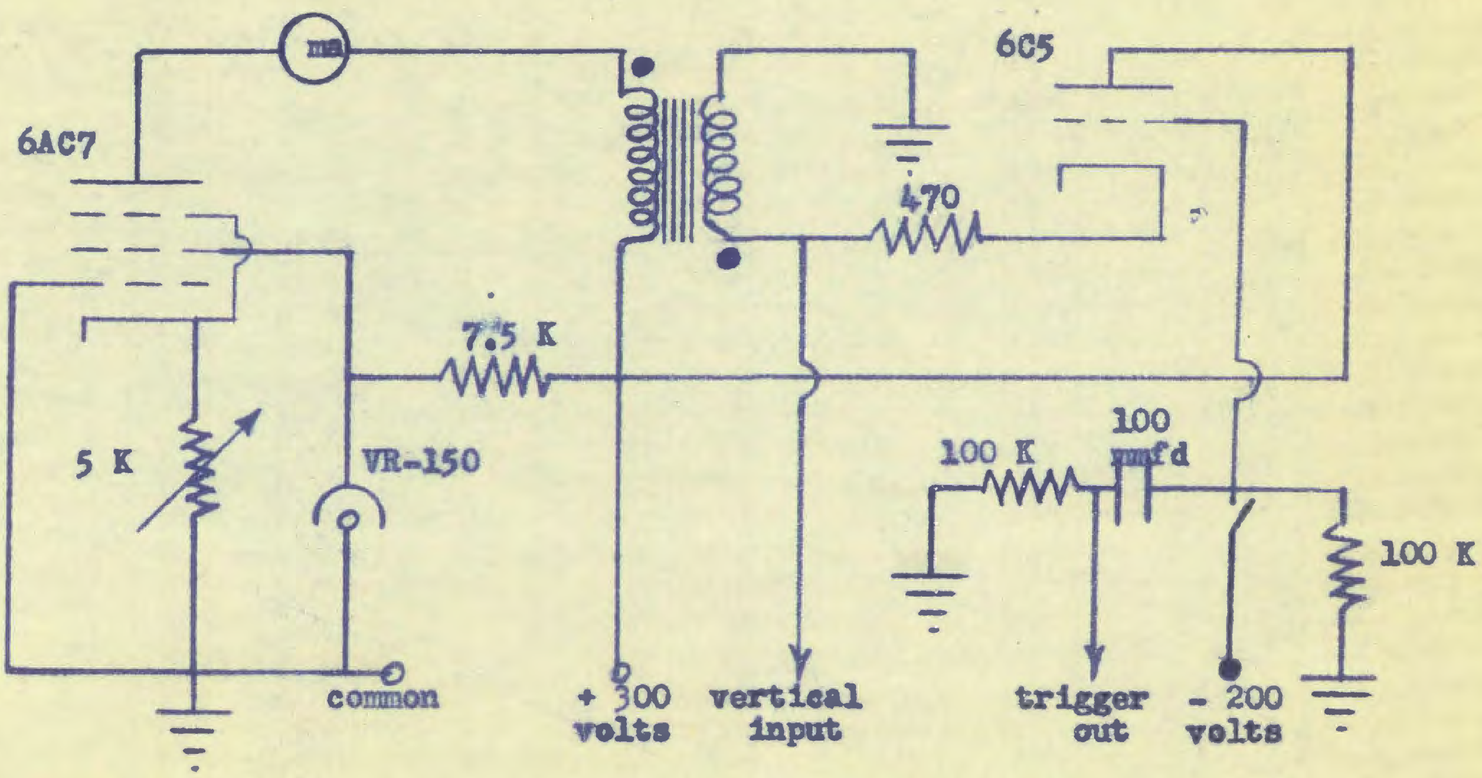

FIGURE 3

CIRCUIT USED TO DETERMINE
RESET FUNCTIONS

control current used to obtain the magnetic amplifier waveforms described in a previous section above. For these waveforms, the horizontal deflection was adjusted to one millisecond per centimeter, giving a total sweep width of ten milliseconds, or slightly more than one half cycle at sixty cycles per second. The second set of data was taken to determine the time for complete reset to take place as a function of applied magnetizing force. The vertical deflection of the oscilloscope was adjusted so that the reset function intersected the zero axis at a sharp angle.

Transfer characteristic. The transfer characteristic was plotted using the circuit of Figure 2, page 35. Control current was adjusted by varying the bias on the constant current tube. The maximum control current used was that which just reduced the output current to its minimum value. The control current was reduced until the triggering action described by Batdorf and Johnson was noted.[8] Past this point, the control current was reduced in increments of one half milliampere until three sucessive settings resulted in the same output current.

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[8] S. B. Batdorf and W. N. Johnson, ''An Instability of Self-Saturating Magnetic Amplifiers Using Rectangular Loop Core Materials,'' Communication and Electronics, 7:223-228, 1953.

IV. CALCULATED DATA

An approximate transfer characteristic was calculated by determining its end points from the published values of coercive force and the experimentally determined magnetizing force necessary to reset the core to negative saturation in one half cycle.

Total circuit resistance. The root-mean-square source voltage was measured open circuit and with the magnetic amplifier connected and adjusted for a firing angle of zero degrees, the average load current was measured. The total circuit resistance was assumed to be the RMS source voltage divided by twice the form factor less the rectifier drop, the entire quantity divided by the average current. This procedure was employed because no RMS alternating current ammeters of sufficient accuracy were available.

Transfer characteristic. No attempt was made to determine accurately the shape of the transfer characteristic, as this has been done elsewhere.[9] Only the maximum value of control magnetizing force resulting in maximum output and that resulting in minimum output were calculated. In other words, the transfer characteristic is placed in its proper position with relation to other measurable

---

[9] Storm, op. cit., pp. 632-634.

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[9] Storm, op. cit., pp. [illegible]

properties of the magnetic core material.

Reference to Figure 1, page 28, shows that a control magnetizing force less than the static coercive force will result in no change of flux, regardless of how long applied, while a value only slightly in excess of the coercive force will result in a flux change to saturation in the opposite direction, provided sufficient time is allowed. Therefore, the maximum value of magnetizing force that results in maximum output will be taken to be the static coercive force of the core material.

Reference to Figure 4, page 43, shows that the flux will be changed from positive to negative saturation in a time determined by the amount of control magnetizing force applied. Any value of control magnetizing force in excess of that required to reset the core to saturation in the opposite direction in one half the period of the supply voltage will not result in a lower minimum output.

The useful range of control current, then, is that which produces magnetizing forces between the static coercive force and the magnetizing force that resets the core to negative saturation in one half the period of the power supply frequency.

properties of the magnetic core material.

Reference to Figure 4, page 24, shows that a control magnetising force less than the static coercive force will result in no change of flux, regardless of how long applied, while a value only slightly in excess of the coercive force will result in a flux change to saturation in the opposite direction, provided sufficient time is allowed. Therefore, the maximum value of magnetising force that results in maximum output will be taken to be the static coercive force of the core material.

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The useful range of control current, then, is that which produces magnetising forces between the static coercive force and the magnetising force that resets the core to negative saturation in one half the period of the power supply frequency.

V. ASSUMPTIONS

Assumptions implicit in the methods stated above are listed in the following paragraphs.

Voltage drops. The load impedance is assumed resistive and lumped in the load resistance. The rectifier is assumed to have a constant forward voltage drop which is independent of load current, and negligible reverse conductance.

Magnetic properties of core material. The static coercive force, saturation flux density and stacking factor are assumed to have the values stated by the manufacturer. The permeability of the core material in the saturation region is assumed negligible.

Power supply. The alternating current power supply used was the sixty cycle power line. Its voltage was monitored during all tests to assure its constancy within one half per cent, and its frequency was assumed to be sixty cycles per second to a high degree of accuracy.

Instruments. All meters used were assumed to read within the accuracy stated on their nameplates. Laboratory standard meters calibrated within three months prior to use were used for all measurements.

CHAPTER IV

DATA

Data taken or calculated in support of the thesis is presented in the following graphs and tables.

Reset functions. Figure 4, page 42, presents the reset functions obtained by the action of the constant direct current without an alternating current supply connected to the circuit. These functions represent the rate of change of flux as a function of time. Ordinates are marked in volts. The values of constant control current chosen as parameters are the same used to obtain the waveforms shown in Figures 5 through 8, page 44. Figure 4 is an actual photograph of the oscilloscopic trace obtained by multiple exposure techniques.

Magnetic amplifier waveforms. Figures 5 through 8, page 44, are the voltage waveforms taken across the gate winding of the magnetic amplifier for four values of firing angle. Ordinates on these waveforms represent voltage. These waveforms were obtained photographically.

Time for complete reset. The control current required to produce reset from positive to negative saturation in a given time is presented in Figure 9, page 45. The data

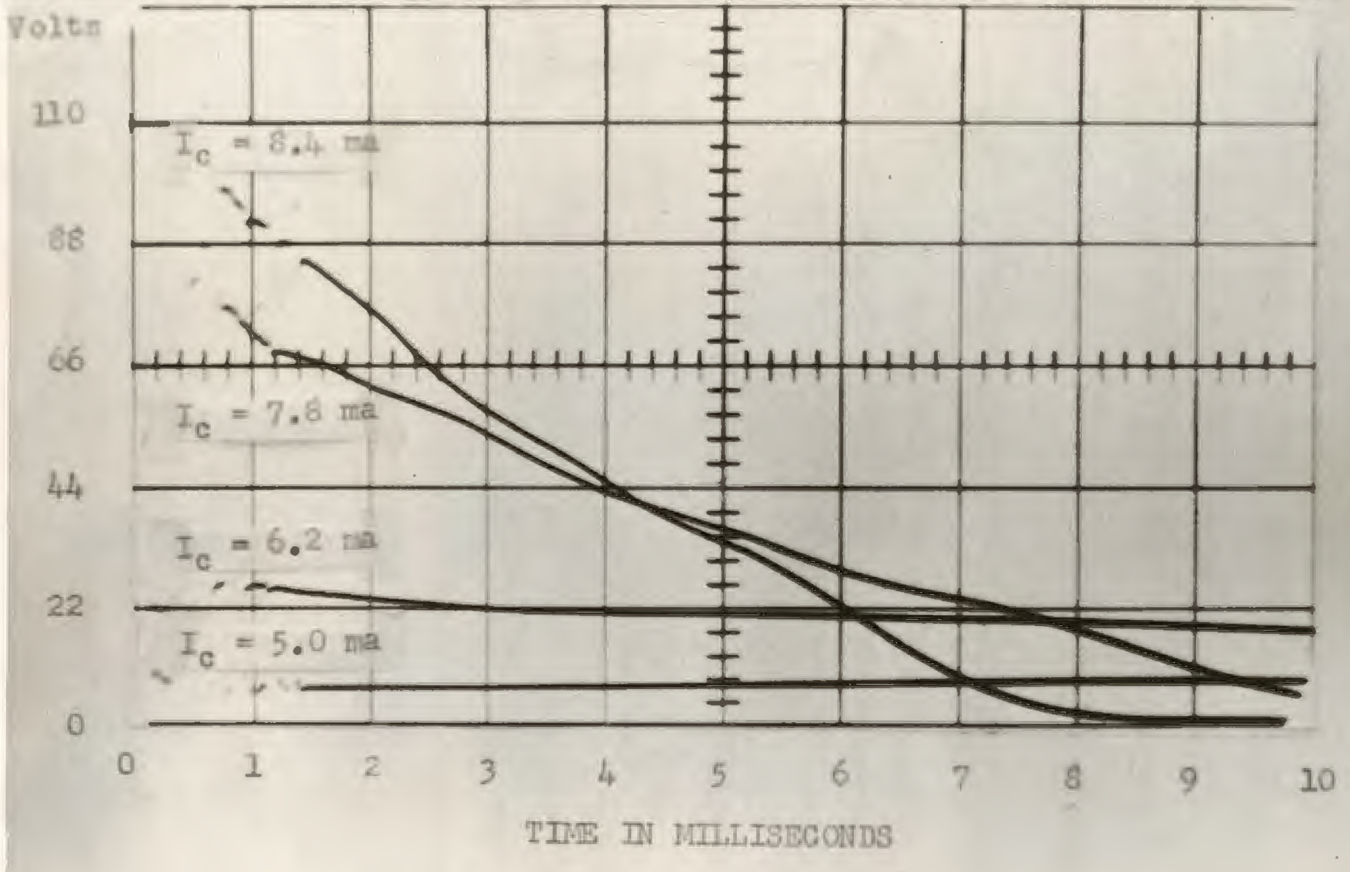

FIGURE 4

RESET FUNCTIONS FOR
SEVERAL VALUES OF MAGNETIZING FORCE

were plotted at the points indicated and connected by a smooth curve.

Transfer characteristic. The transfer function was plotted as load current versus control current. Control current corresponding to the static coercive force of the core material was indicated for reference. Likewise, the control current producing reset from positive to negative saturation in one half the period of the power supply frequency obtained from Figure 4 or Figure 9 was plotted for reference.

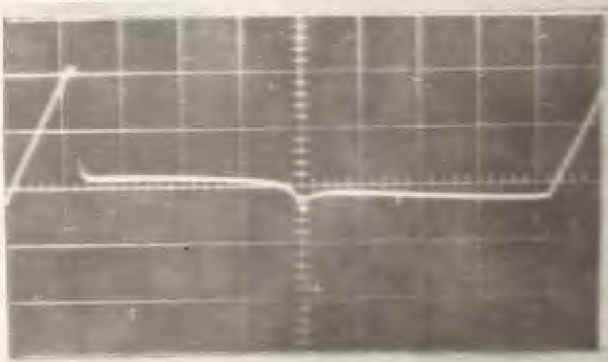

FIGURE 5
GATE WINDING WAVEFORM
Ic = 5.0 ma
E_{pk} = 48 volts

FIGURE 6
GATE WINDING WAVEFORM
Ic = 6.2 ma
E_{pk} = 71 volts

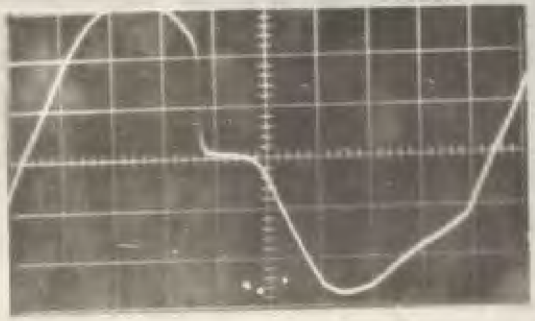

FIGURE 7
GATE WINDING WAVEFORM
Ic = 7.8 ma
E_{pk} = 71 volts

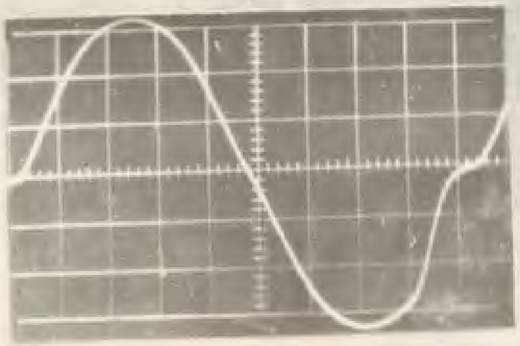

FIGURE 8
GATE WINDING WAVEFORM
Ic = 8.4 ma
E_{pk} = 71 volts

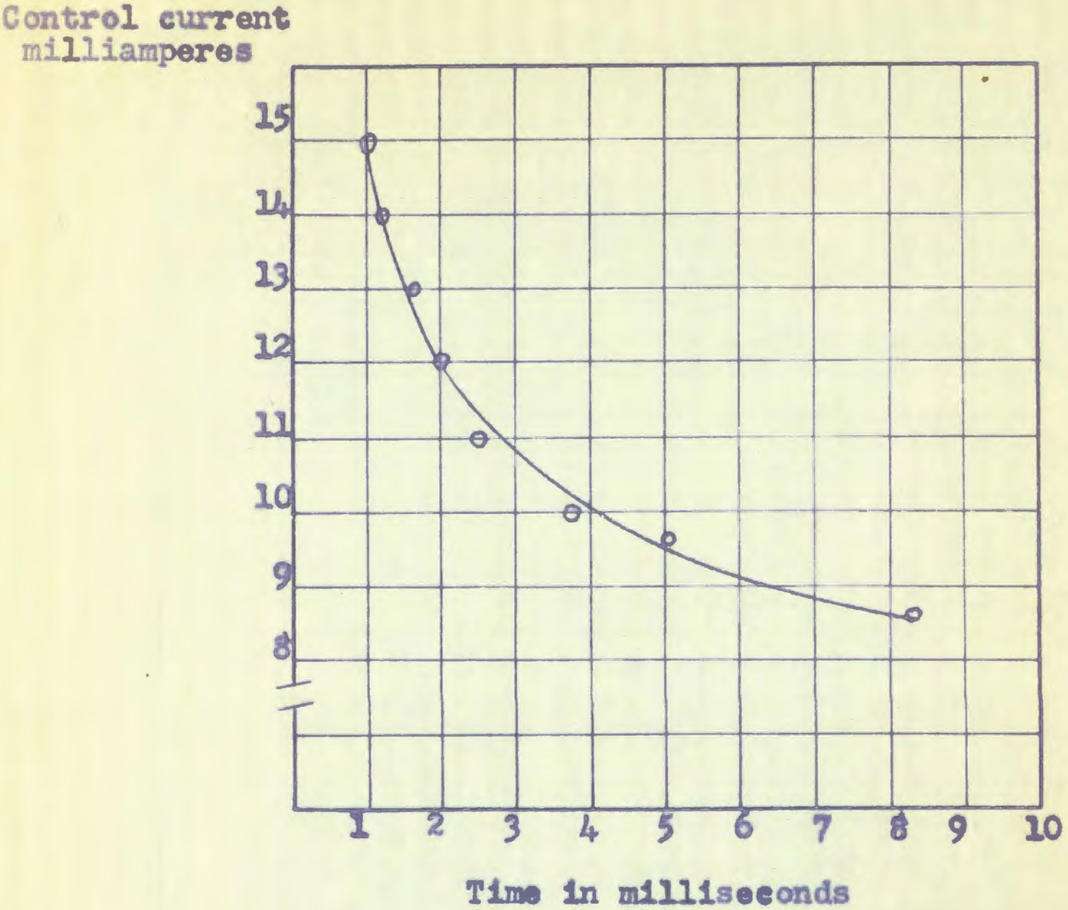

FIGURE 9

CONTROL CURRENT REQUIRED TO CHANGE FLUX FROM POSITIVE TO NEGATIVE SATURATION IN A GIVEN TIME

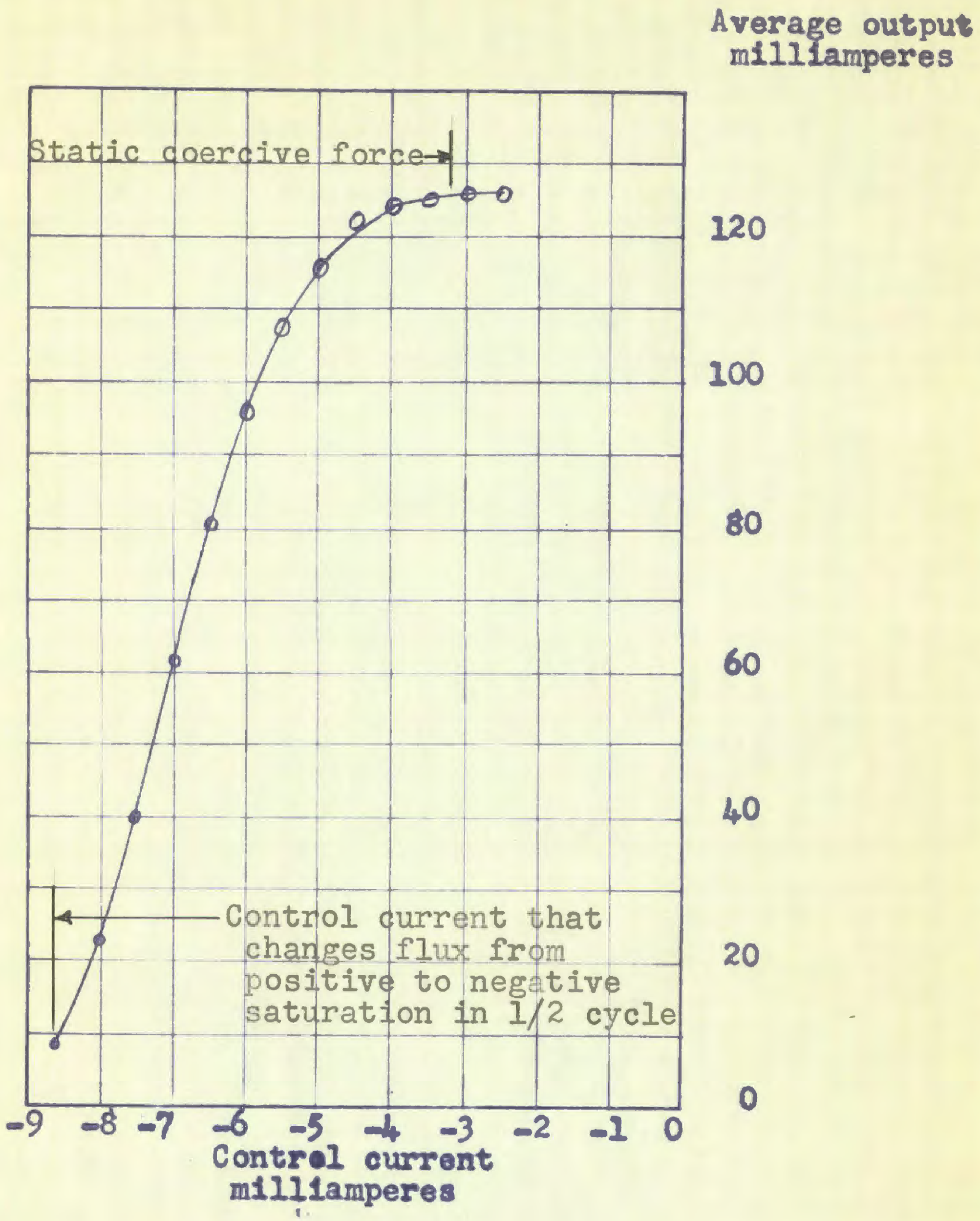

FIGURE 10

TRANSFER CHARACTERISTIC

CHAPTER V

CONCLUSIONS

Conclusions reached from the study are, (1) the circuit is reset by constant current to a degree determined by the amplitude and frequency of the alternating current supply, and (2) a plot of the time required for reset to negative saturation from positive saturation as a function of constant magnetizing force would be an aid to the design of magnetic amplifiers. This plot, along with the static coercive force, would place the top and bottom of the transfer characteristic in their proper relation to the origin of the B-H function of the core material.

I. CIRCUIT OPERATION

A given amount of control current will produce a resultant change during the reset cycle. The flux present in the core at the beginning of the following gating cycle determines the firing angle, and hence, the average current delivered to the load during this gating cycle.

Attention is invited to the two lower curves of Figure 4, page 42. It is seen that the time rate of change of flux is approximately constant. Comparison with the waveforms produced during the reset cycle of the magnetic amplifier, Figures 5 and 6, page 44, show wave shapes

having the same shape and magnitude, with one important exception: a sharp discontinuity followed by a radical change in slope occurs near the end of the reset cycle. This latter portion of the reset function is the supply voltage. Since the voltage generated by the control winding exceeds the supply voltage at the time of this discontinuity, the rectifier finds its terminal voltages such that it conducts, applying the supply voltage across the gate winding. The flux in the core then changes at a rate determined by the supply voltage, much in the same manner as the Ramey circuit, changing at zero lines per second when the supply voltage reaches zero.[1] Had the same constant magnetizing force been applied, but a higher frequency supply voltage used, the supply voltage would have fallen below the reset function at an earlier time. The area under the reset function and hence the flux change during the reset cycle, would have been less per cycle. Conversely, a higher magnetizing force would have been necessary to produce the same flux change in the shorter time allowed by the higher frequency.

With the higher values of firing angle illustrated in Figures 7 and 8, page 44, the reset function appears to

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[1] R. A. Ramey, ''On the Mechanics of Magnetic Amplifier Operation,'' Naval Research Laboratory Report Number 3799, United States Department of Commerce, Washington 25, District of Columbia, January 22, 1951.

having the same shape and magnitude, with one important exception: a sharp discontinuity followed by a radical change in slope occurs near the end of the reset cycle. This latter portion of the reset function is the supply voltage. Since the voltage generated by the control winding exceeds the supply voltage at the time of this discontinuity, the rectifier finds its terminal voltage such that it conducts, applying the supply voltage across the gate winding. The flux in the core then changes at a rate determined by the supply voltage, much in the same manner as the Ramey circuit,[1] changing at zero flux and [illegible] when the supply voltage reaches zero. Had the same constant magnetizing force been applied, but a higher frequency supply voltage used, the supply voltage would have fallen below the reset function at an earlier time. The area under the reset function and hence the flux change during the reset cycle, would have been less per cycle. Conversely, a higher magnetizing force would have been necessary to produce the same flux change in the shorter time allowed by the higher frequency.

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be sinusoidal during the first part of the reset cycle. Reference to corresponding curves in Figure 4 shows that initially the constant current rate of change has a high value. The implication is that the rectifier was so biased during this interval that the supply voltage was applied across the gate winding. A discontinuity was noted at approximately two hundred seventy degrees in Figure 7, followed by a waveform of an irregular nature, and again near the end of the reset cycle, the supply voltage takes control. Figure 8 exhibits no sharp discontinuities, but the ''trailing edge'' of its reset function is clearly not sinusoidal, exhibiting much the same type curvature as the 8.4 milliampere curve in Figure 4 as it approaches zero rate of change.

The second mode of resetting is not so amenable to prediction as that noted for small to intermediate values of firing angles. It has been shown in the literature that constant current reset functions obtained from initial conditions other than saturation differ greatly in shape from those obtained when the core is initially saturated.[2] Therefore the simple ''gating'' process described above for the case of small firing angles does not appear to correlate

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[2] H. Huhta, ''Flux Resetting Characteristics of Several Magnetic Materials,'' Communication and Electronics, 12:113, 1954.

be sinusoidal during the first half of the reset cycle. Reference to corresponding curves in Figure 4 shows that initially the constant current rate of change has a finite value. The implication is that the core flux was changed during this interval that the supply voltage was applied across the gate winding. A discontinuity was observed at approximately two hundred seventy degrees in Figure 7, followed by a waveform of an irregular nature, and again near the end of the reset cycle, the supply voltage takes control. Figure 8 exhibits no sharp discontinuities, and the ''trailing edge'' of the reset function is clearly non-sinusoidal, exhibiting much the same type of curvature as the 8.4 milliampere curve in Figure 4 and a monotonous slow rate of change.

The second mode of resetting is not so amenable to prediction as that noted for small to intermediate values of firing angles. It has been shown in the literature that constant current reset functions obtained under initial conditions other than saturation differ greatly in shape from those obtained when the core is initially saturated.[1] Therefore the simple ''lifting'' process described above for the case of small firing angles does not appear to cover this

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[1] K. Gupta, ''Influence of [illegible] Characteristics of Several Magnetic Materials,'' *Communication and Electronics*, 12:112, 1954.

too well with the constant current reset functions, although a similar process is undoubtedly taking place.

II. DESIGN PROCEDURE

The shape of the transfer characteristic has been described by Storm.[3] However, its relation to the static hysteresis loop was not made entirely clear, and knowledge of the width of the dynamic hysteresis loop at the power supply frequency was presumed. Difficulties encountered in obtaining dynamic hysteresis loops for non-standard power supply frequencies have been previously stated.[4]

Arguments stating the role of the static hysteresis loops in magnetic amplifier design have been previously presented.[5]

The same magnetizing force which resulted in a firing angle of one hundred eighty degrees in the magnetic amplifier also changed the flux in the same core from positive to negative saturation in a time equal to one half cycle of the sixty cycle power supply frequency. Although only one core was available for test, this correlation was felt too

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[3] H. F. Storm, ''Theory of Magnetic Amplifiers with Square-Loop Core Materials,'' Communication and Electronics, 9:643, 1953.

[4] *Cf*. *ante*, p. 4.

[5] *Cf*. *ante*, p. 39.

close to be the result of coincidence. If the manufacturer of core materials could publish for each heat and shape of core a curve similar to Figure 9, page 47, along with the static coercive force, the designer would have at his disposal information applicable to a wide range of power supply frequencies and which would enable him to determine the useful range of control current in a given magnetic amplifier.

III. LIMITATIONS AND SUMMARY

It is acknowledged that insufficient data is herein presented to conclude finally that the constant magnetizing force required to change the flux state of a core from positive to negative saturation in a time equal to one half cycle will always be the same required to produce a firing angle of one hundred eighty degrees in a magnetic amplifier at that frequency. However, excellent correlation was obtained for one case, and due to the usefulness of the results, appears to warrant further study.

Operation of the half-wave, self-saturable magnetic amplifier during its reset cycle can be explained, at least in a qualitative manner, by consideration of a gating process occuring between the constant current waveforms of Figure 4 and the sinusoidal supply voltage.

close to be the result of coincidence. If the manufacturers of core materials could publish for each heat and type of core a curve similar to Figure 9, page 87, along with the static coercive force, the designer would have at his disposal information applicable to a wide range of power supply frequencies and which would enable him to determine the useful range of control current in a given magnetic amplifier.

III. LIMITATIONS AND SUMMARY

It is acknowledged that insufficient data are herein presented to conclude finally that the average magnetizing force required to change the flux density of a core from positive to negative saturation in a time equal to one half cycle will always be the same required to produce a firing angle of one hundred eighty degrees in a magnetic amplifier at that frequency. However, excellent correlation was obtained for one case, and due to the usefulness of the results, appears to warrant further study.

Operation of the half-wave, self-saturable magnetic amplifier during the reset cycle can be explained, at least in a qualitative manner, by consideration of a [illegible] process occurring between the capacitance of the circuit of Figure 4 and the sinusoidal supply voltage.

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