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

William W. Lee

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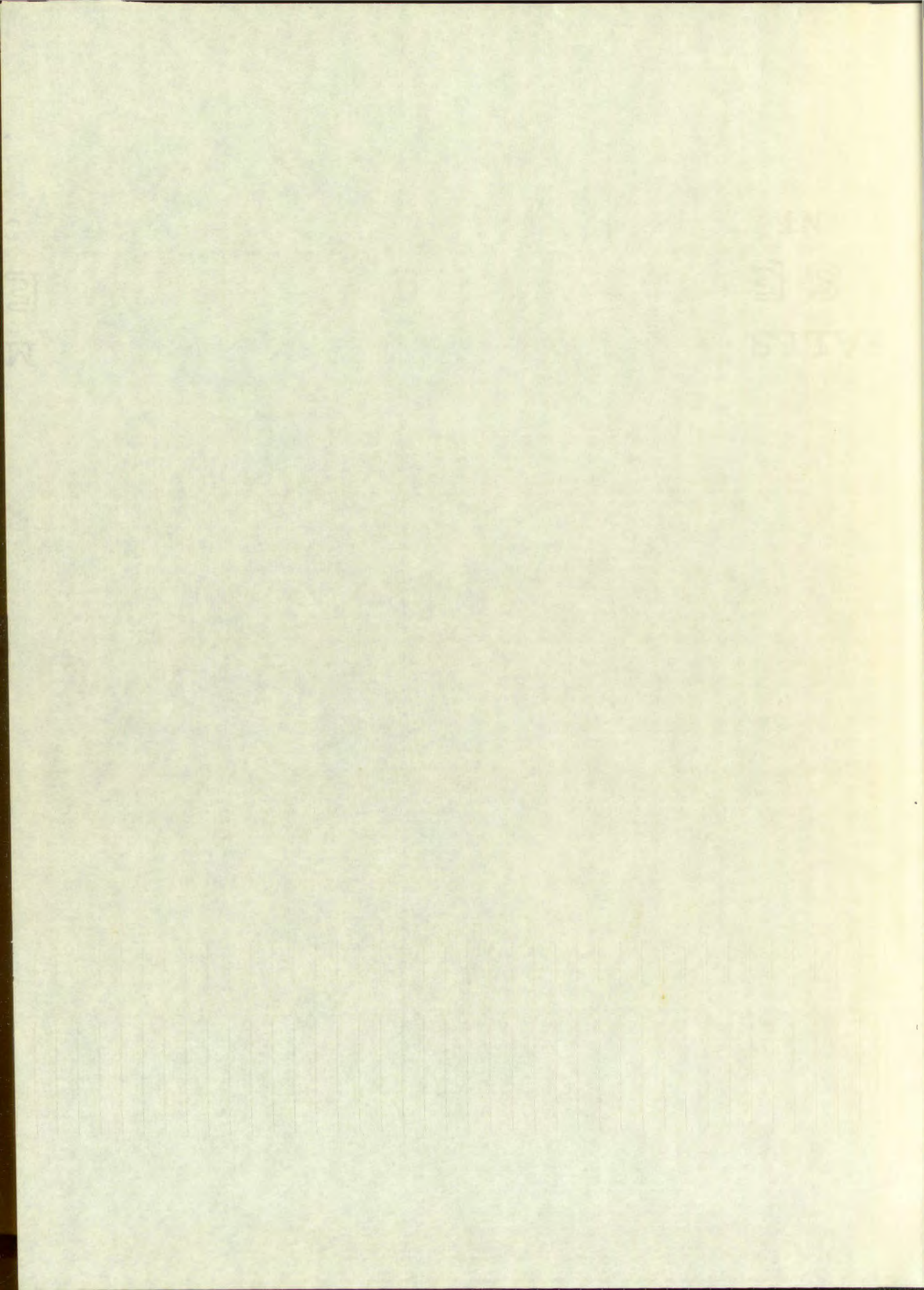


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A STUDY OF THE RESET CYCLE OF A HALF-WAVE SELF-SATURABLE  
MAGNETIC AMPLIFIER

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

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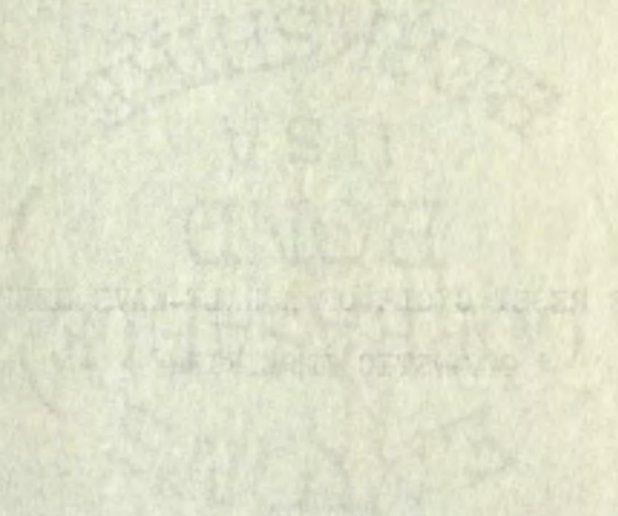
In Partial Fulfillment  
of the Requirements for the Degree  
Master of Electrical Engineering

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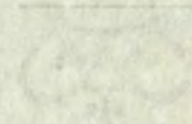
by  
William W. Lee, Jr.

June 1958





A STUDY OF THE REACTIVITY OF A...  
...  
...



A Thesis  
Presented to

the Faculty of the Department of Chemical Engineering  
University of New Mexico

In Partial Fulfillment

of the Requirements for the degree  
Master of Electrical Engineering

by  
William S. ...  
June 1954

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. Wasteller*

DEAN

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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.

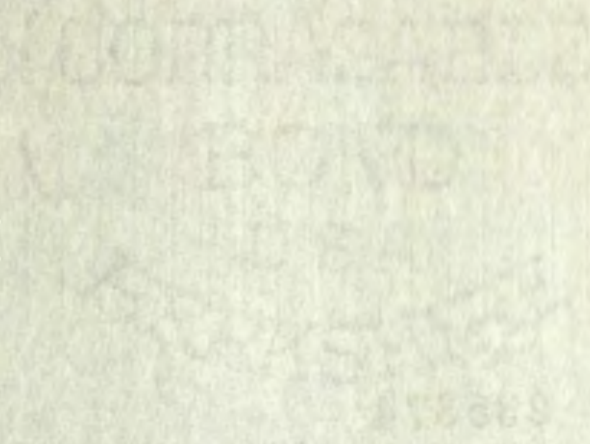
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ACKNOWLEDGMENTS

This thesis was written while on active duty with the U. S. Navy, assigned to a research position at the Naval Research Laboratory and laboratory facilities necessary for the completion of this work were available only through the cooperation of many individuals.

Particular appreciation is extended to Mr. Leslie R. Gower of the University of Tennessee for his assistance in locating reference material, and to Mr. James H. Gandy and Mr. J. L. Gortney for making available the only suitable laboratory facilities within easy reach of the writer.

Gratitude is also expressed to the Arnold Engineering Development Center, Dayton, Ohio, for providing the core used in the experimental phase of the investigation.





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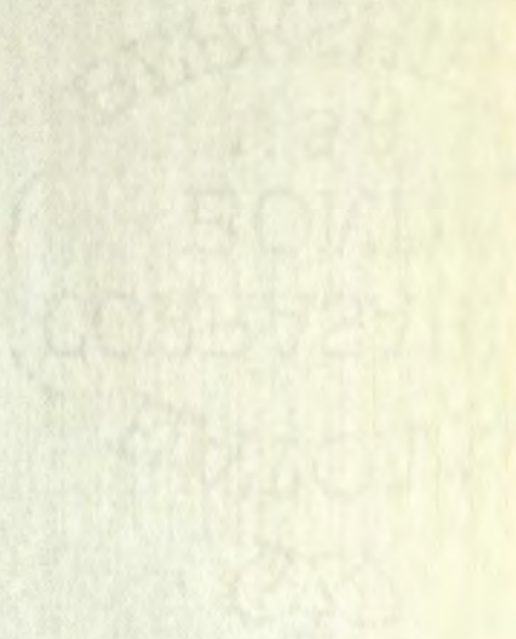
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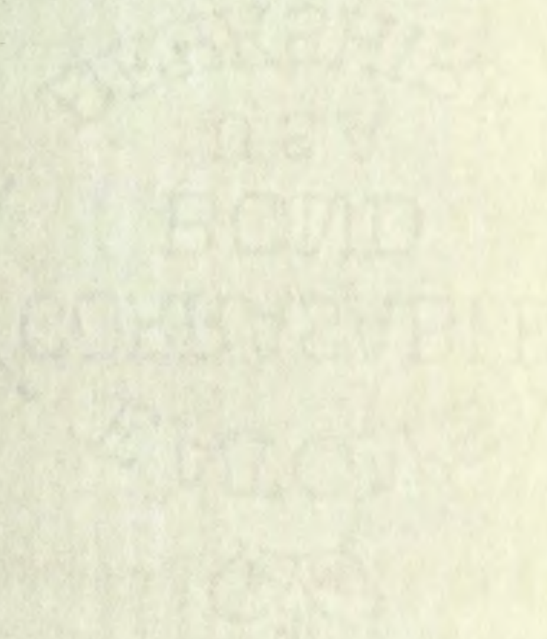
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GOVERNMENT  
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## CHAPTER I

### 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.<sup>1, 2</sup> Although patented in its basic form in 1919,<sup>3</sup> 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.

---

<sup>1</sup> H. B. Rex, "Bibliography of Transducers, Magnetic Amplifiers, etc.," Instruments, 21:332, 352-362, April, 1948.

<sup>2</sup> J. G. Miles, "Bibliography of Magnetic Amplifier Devices and the Saturable Reactor Art," AIEE Transactions, 70:2104-2123, Part II, 1951.

<sup>3</sup> J. Jonas, "Apparatus for Regulating the Voltage of Metal Vapor Rectifier Installations," United States Patent 1,434,346, issued 4 October, 1920.



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. The first has been published since that time, and the second appeared in its basic form in 1952, and the bibliography therein does not to have been widely understood or used. In 1952, II, after which time many articles, books, and technical operation appeared. These articles, books, and technical results which are, for the most part, fairly good, but mental data, neglect entirely or touch lightly on the operation of the circuit having the most effect.

J. H. B. Rex, "Magnetic Amplifiers," etc., McGraw-Hill, 1951, April, 1951.

J. L. Jones, "Magnetic Amplifiers," McGraw-Hill, 1952, 70:2104-2123, Part II, 1952.

J. L. Jones, "Magnetic Amplifiers," McGraw-Hill, 1952, Patent 1,831,740, Dec. 2, 1930.



## 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



I. DEFINITION OF VARIOUS TERMS

Constant current reset. A method whereby the current is reset to some predetermined value by means of a reset current function acting on the load circuit after the winding.

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

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

Firing angle. The angle of the wave which is the phase at which the core saturates, thereby shorting power supply voltage across the load.

Gate 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 electro-mechanical device employing the principle of saturation whereby power delivered to a load may be controlled by a small 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.

Significance of the study. That the operating



during which the flux is zero. The flux is zero because the  
full load current is sufficient to saturate the core.

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

Self-saturation. A phenomenon in magnetic materials  
whereby the supply voltage is insufficient to re-magnetize  
the gate winding from cycling to one core during the reset  
cycle.

Transfer function. A parameter which is a function  
whereby some property of the output is expressed as a function  
of some property of the input.

### 11. THE PROBLEM

Statement of the problem. It was the purpose of this  
study (1) to investigate the reset cycle of a self-saturating  
self-saturable magnetic amplifier by analytical means and  
the irregular voltage behavior appearing across the gate  
winding during reset; (2) to determine the conditions for  
this analysis a more satisfactory design method than those  
now available. Conditions of constant current reset were  
employed and the core material used was a nearly rectangular  
hysteresis loop. Hysteresis loops only are considered.

Significance of the study. It is the purpose of this



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<sup>4</sup> 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.<sup>5</sup> There is nothing, of course, to preclude the application of

---

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

<sup>5</sup> 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.



hysteresis loop of the hysteresis loop, from which the  
netic amplifier hysteresis loop is obtained by adding  
gators. These hysteresis loops are obtained by adding  
among them core magnetic, and the hysteresis loop  
power supply frequency, and the hysteresis loop  
other external circuitry. The hysteresis loop is  
to approximate transfer characteristics and hysteresis  
discussed, and in fact, the hysteresis loop is  
used to relate various types of hysteresis loops  
curves arise when operating as the hysteresis loop  
this purpose. Obtaining the hysteresis loop is a  
be a problem. At least the core magnetic hysteresis  
published detailed hysteresis loops. On the other hand  
direct current, since the hysteresis loop is  
mittedly these appear to be the hysteresis loop  
frequencies in this case, however, over a wide  
delivering they cycles are shown in Figure 1, which  
frequencies from 50 to 500 cycles per second, and  
nothing, of course, to provide the hysteresis loop

\* The Arnold Engineering Research Laboratory, Illinois  
Bulletin TO-1011, Properties of Hysteresis, 1957  
Springer, March 1957, Technical Report, 1957.

† World Electrical Engineering Corporation, Bulletin  
States Department of Commerce, Washington, D.C., 1957  
October 1957, titled on Hysteresis Loop  
Engineers, card address, 1957, Technical Report  
Corporation, New York, March 1957, 1957.



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.<sup>6</sup>

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

---

<sup>6</sup> Cf. post, p. 12.



frequency in the range of 400 cycles per second...  
suiting owing in weight...  
equipment. It is...  
the frequency desired, it would be necessary to...  
requiring special equipment and...  
Having obtained a... loop, the...  
only partially solved, neither the...  
loop represents the transfer...  
function lying between...  
Therefore, a method of...  
characteristic independently of...  
desirable, even though it...  
How many control...  
III. ORGANIZATION OF THE...  
The remainder of the...  
as follows:

### Chapter II - Review of the Literature

from the technical literature...  
were reviewed. Particular...  
discussions dealing with...  
parties and...  
A section on the...  
of the...  
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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.



amplifier was included.

Chapter III - Method. The use of an oscilloscope in

the problem, the methods used to obtain data, and the use of special equipment and the details, along with experimental results with special reference for them when applicable.

Chapter IV - Results. The results obtained in the study are

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.<sup>1, 2</sup> Many publications, especially those of the American Institute of



REVIEW OF EARLY WORK

A complete review of the literature known in the general subject of magnetic amplifiers would be a major undertaking. Fortunately, however, a number of papers have been published in this country and abroad on the subject, so that nothing of the general nature covering magnetic amplifiers devices. Therefore, this review will be limited to those general areas which have bearing on the thesis topic, that is, a general review of the electrical properties of the magnetic amplifier and saturation reactor etc. is given. Several papers which are directly related to the subject are cited on the general subject of self-saturable magnetic amplifiers are discussed, and finally those few articles dealing directly with the subject of the thesis are reviewed. This latter group includes material on the subject of testing of magnetic amplifier materials.

Historical Development

As was previously stated, the technical literature of the electrical engineering contains a wealth of information on magnetic amplifiers and related devices. The bibliography of the thesis is limited to those thousands of articles which are of interest to the thesis, especially those which are of a nature which are of



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.<sup>3</sup> 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  $\pm 0.5$  per cent by a nulling process.<sup>4</sup>

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

---

<sup>1</sup> H. B. Rex, 'Bibliography of Transducers, Magnetic Amplifiers, etc.,' Instruments, 21:332, 352-362, April, 1948.

<sup>2</sup> J. G. Miles, 'Bibliography of Magnetic Amplifier Devices and the Saturable Reactor Art,' AIEE Transactions, 70:2104-2123, Part II, 1951.

<sup>3</sup> C. F. Burgess and B. Frankenfeld, 'Regulation of Electrical Circuits,' United States Patent 720,884, issued February 17, 1903.

<sup>4</sup> H. J. Ryan, 'The Transformer for Measuring Large Direct Currents,' AIEE Transactions, 20:169-183, 1901.



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SECRET

Electrical Engineering, Department of Electrical Engineering, University of California, Berkeley, California, U.S.A.

These devices have been developed and are described in the following paper:

The first practical application of the principle of the first device appeared in the form of a magnetic amplifier, patented by the author and others in 1947. This device is described in the paper "Magnetic Amplifier with Automatic Control of Direct Current", published in the Proceedings of the IRE, Vol. 35, No. 1, January 1947.

The principle of the first device is based on the fact that the magnetic flux in a closed magnetic circuit can be controlled by a direct current. This principle is described in the paper "Magnetic Amplifier with Automatic Control of Direct Current", published in the Proceedings of the IRE, Vol. 35, No. 1, January 1947.

The principle of the first device is based on the fact that the magnetic flux in a closed magnetic circuit can be controlled by a direct current. This principle is described in the paper "Magnetic Amplifier with Automatic Control of Direct Current", published in the Proceedings of the IRE, Vol. 35, No. 1, January 1947.

At about the same time, the author was engaged in the study of the properties of assemblies of magnetic amplifiers. It was found that the properties of such assemblies are very different from those of individual amplifiers. This is described in the paper "Properties of Assemblies of Magnetic Amplifiers", published in the Proceedings of the IRE, Vol. 35, No. 1, January 1947.

and embodied in a device which is described in the paper "Properties of Assemblies of Magnetic Amplifiers", published in the Proceedings of the IRE, Vol. 35, No. 1, January 1947.

100-1000 cycles could be generated with a frequency of 100-1000 cycles per second by a rotating process.

The first device described in a paper published in the Proceedings of the IRE, Vol. 35, No. 1, January 1947.

adjustable magnetic amplifier, as described in the paper "Adjustable Magnetic Amplifier", published in the Proceedings of the IRE, Vol. 35, No. 1, January 1947.

1. H. B. Ryan, "Magnetic Amplifier with Automatic Control of Direct Current", Proceedings of the IRE, Vol. 35, No. 1, January 1947.

2. J. G. Mian, "Properties of Assemblies of Magnetic Amplifiers", Proceedings of the IRE, Vol. 35, No. 1, January 1947.

3. G. F. Taylor, "Adjustable Magnetic Amplifier", Proceedings of the IRE, Vol. 35, No. 1, January 1947.

Electrical Engineering, Department of Electrical Engineering, University of California, Berkeley, California, U.S.A.

February 14, 1947.

A. H. J. Ryan, "Direct Current Control of Magnetic Amplifier", Proceedings of the IRE, Vol. 35, No. 1, January 1947.



1919 and was used to control the output of metal vapor rectifiers.<sup>5</sup>

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.<sup>6</sup> 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.<sup>7, 8</sup>

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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<sup>5</sup> J. Jonas, "Apparatus for Regulating the Voltage of Metal Vapor Rectifier Installations," United States Patent 1,434,346, issued 4 October, 1920.

<sup>6</sup> W. Kramer, "A Simple Direct-Current Type of Instrument Transformer Having Real Current-Transformer Properties," Elektrotechnische Zeitschrift, 58:1308-1313, 1937, Berlin.

<sup>7</sup> A. O. Black, "The Effect of Core Material on Magnetic Amplifier Design," Proceedings of the National Electronics Conference, 4:427, April, 1948.

<sup>8</sup> 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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applier type control systems installed in the German  
Cruiser Prinz Eugen resulted primarily in measurements.  
Among other German vessels who constructed the  
field of knowledge on magnetic fields, Kramer's  
to be the first to raise the question of his device.

J. J. Jones, "The German Control System for the  
of Metal Vapor Rectifier," Patent 2,431,100,  
Patent 2,431,100, issued 1949.

W. Kramer, "The German Control System for the  
Instrument Transformer Having a Self-Excited  
Properties," Elektronische Nachrichten,  
1937, Berlin.

V. A. O. Black, "The German Control System for the  
Magnetic Amplifier Device," Electronic  
Electronics Conference, 1947.

The material on magnetic fields was taken from  
W. A. Geysen, Magnetic Amplifier, New York, 1947,  
Hill Book Company, Inc., pp. 6-21.



to the properties of the magnetic material.<sup>9</sup>

Literature devoted to the self-saturable circuit.

Among the first to describe the property of self-saturation was Dornhoefer.<sup>10</sup> 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 absorption 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.<sup>11</sup>

Dornhoefer derives a relation showing the dependence

<sup>9</sup> 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.

<sup>10</sup> W. J. Dornhoefer, "Self-Saturation in Magnetic Amplifiers," AIEE Transactions, 68:835-850, Part II, 1949.

<sup>11</sup> Ibid., p. 837.



to the properties of the magnetic material.

Literature devoted to the self-energized reactor

Among the first to describe the property of self-energized reactor was Dornhoefer. In his work he treated the self-energized reactor as a transformer. Previous writers described the self-energized reactor as a transformer of the energy of applied magnetic field by means of additional windings carrying load current.

He summarized the results of his work as follows:

The anode winding is capable of generating a large electromotive force due to magnetic flux changes. For small values of anode current, the anode voltage is positive, and when the supply voltage becomes positive, a positive slope, and after a certain time the anode voltage appears across the grid winding which may be thought of as a transformer. The anode reaction is a voltage which must be associated with a change of magnetic flux in the reactor core. When the anode current reaches a certain critical value, the reactor is fired, and the reactor no longer carries current. The anode current and the output anode current are all value to a value sufficient to start the reactor as approximately equal to the supply voltage.

Dornhoefer gave a relation showing the dependence

9. Dr. Dornhoefer, "On the Theory of the Self-Energized Reactor," Proceedings of the IRE, Vol. 3, No. 1, p. 10, 1915.  
10. W. J. Dornhoefer, "Self-Energized Reactor in Amplifiers," IRE Transactions, Vol. 3, No. 1, p. 10, 1915.



of average output voltage on the flux present in the core at the start of the gating cycle.<sup>12</sup> 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.<sup>12</sup> Rather poor correlation 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.<sup>12</sup> Later writers do not concur in this last assumption.<sup>13, 14</sup>

In 1953, Storm published an analysis of the full wave circuit with low control circuit impedance, assuming a rectangular hysteresis loop.<sup>15</sup> 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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<sup>12</sup> Ibid., p. 845.

<sup>13</sup> Cf. post, p. 12.

<sup>14</sup> Cf. post, p. 21.

<sup>15</sup> H. F. Storm, 'Theory of Magnetic Amplifiers with Square Loop Core Materials,' Communication and Electronics, 9:629-640, 1953.



of average output voltage on the line between the core  
 at the start of the gating cycle. In order to predict  
 the transfer function of the magnetic amplifier, an attempt  
 to relate the initial flux to a corresponding control mag-  
 netizing force by using the upper branch of the magnetic  
 hysteresis loop.<sup>12</sup> Rather, our conclusion was based  
 between this predicted transfer characteristic and the  
 transfer characteristic observed experimentally. This  
 attributed this discrepancy to the finite width of  
 the core, and felt that only one constant time delay  
 be neglected.<sup>13</sup> Later studies of the core in this  
 assumption.<sup>14, 15</sup>

In 1953, Storm published an analysis of the hysteresis  
 circuit with low control circuit inductance, resulting in  
 rectangular hysteresis loop.<sup>16</sup> In this, a complete transfer  
 characteristic is proposed which includes both gates 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 also included in the analysis.

- 12. IEEE Trans. p. 642.
- 13. ibid. p. 644.
- 14. ibid. p. 645.

15. H. F. Storm, "Theory of magnetic amplifiers with  
 square loop core inductors," Quarterly Review and Progress  
 9:629-640, 1953.



showing the deterioration of gain that results is derived. In a discussion on this analysis, Lord observes that better correlation 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.<sup>16</sup> 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.<sup>17</sup>

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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<sup>16</sup> Ibid., p. 637.

<sup>17</sup> Henry Lehmann, 'Predetermination of Control Characteristics of Half-Wave Self-Saturated Magnetic Amplifiers,' AIEE Transactions, 70:2097-2103, Part II, 1951.



showing the deterioration of the material in a  
 in a discussion on this subject, but on the other hand  
 correlation between analysis and observation. It is  
 occurs for the case of some special kind of very  
 hysteresis loop when the observation is made by  
 characteristic is displaced to the left by an amount  
 to one-half the static hysteresis force. In many cases  
 states that the transfer characteristic may be approximated  
 by the major hysteresis loop as modified by a hysteresis  
 factor whose magnitude is dependent on the width of the  
 static loop, the thickness of the core and the  
 and residual losses.

Latham used an entirely experimental approach to  
 the problem of determining the transfer characteristic.

He states:

...The  $B_0 - H_0$  relationship... is a...  
 the  $B_0 - H_0$  relationship... is a...  
 between these two curves. This relationship can be  
 obtained only by actually plotting the loop of the  
 better type of the minor hysteresis loop over which  
 the core operates... This two must be obtained at  
 the actual frequency of operation of the material.  
 At any other frequency the only current allowed will  
 different and the minor hysteresis loop obtained will  
 not be those over which the core will normally operate.

to Ibid., p. 137.

Dr Henry Latham, "Characteristics of Half-Wave Rectifiers on Ferrite  
 AIEE Transactions, 1930-31, Part II, p. 137.



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.<sup>18</sup> 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.<sup>19</sup> He describes an installation where magnetic amplifiers are employed in measuring and totalizing for measuring the large currents

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<sup>18</sup> C. W. Lufcy, A. E. Schmid and P. W. Barnhard, "An Improved Magnetic Servo Amplifier," Communication and Electronics, 2:281-289, 1952.

<sup>19</sup> E. A. Downing, "Magnetic Amplifiers in Metering Direct Current on Electrolytic Cell Lines," Applications and Industry, 12:93-96, May, 1954.



Many reports appear in the literature regarding applications in which the half-wave circuit may be used because of its unique properties of reliability. Early writers point out the greatest disadvantage of the magnetic amplifier as the relatively slow time response. However, Lacey, Schmidt and Barbrae recognized that the response time of the half-wave circuit is slower than the cycle of the power supply frequency. They reason that the time delay is due to the high inductance of the control winding in the half-wave circuit. The reason is obvious in that from a high resistance source, and with the inductance, the inductance of the control winding is negligible, allowing the control current to reach the grid of the tube in a short time. They then propose a two half-wave circuit with all control windings that are connected in series.

A use of magnetic amplifiers in industrial applications is pointed out by Lacey. The description in installation where magnetic amplifiers are employed in measuring and controlling temperature in the furnace circuit.

10 C. W. Lacey, A. Schmidt and J. Barbrae, "An Improved Magnetic Amplifier," Electronics and Electronics, 2:281-282, 1949.

10 E. A. Downing, "Magnetic Amplifiers in Industrial Direct Current on Electrolytic Cell Plants," Electronics and Industry, 12:25-26, May, 1951.



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.<sup>20, 21</sup> 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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<sup>20</sup> Dornhoefer, op. cit.

<sup>21</sup> Storm, op. cit.



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Flowing in electrical circuit. The electrical circuit was  
the great expense involved in the fabrication of a very  
large coil winding machine. At a cost of \$100,000, the machine  
the saving of the \$100,000 will be offset by such a saving  
annually.

The theoretical papers previously discussed are  
primarily with the transfer of heat in a liquid or vapor  
taking place during the cooling cycle. It was previously  
noted that the average rate of cooling is not too high  
flux present in the case of the cooling of the liquid  
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 initial current and length  
the control magnetic force by some function of the position  
the static and dynamic forces of the core material. It was  
further established that even in the presence of magnetic  
the core material could be reasonably used to transfer heat  
of this transfer characteristic was the same as that of  
rectifier leakage, particularly during the cooling cycle and other  
factors which might be difficult to ascertain.

The above problems may have been solved by the following:

20 December, 1944  
21 Secret, pp. 411



Ramey's investigations.<sup>22</sup> 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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<sup>22</sup> 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.



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Raymer's investigations... in a report for the Naval Research Laboratory in 1951, he reported that (1) the firing angle remains constant and (2) the flux from some initial value to zero during the entire cycle then (3) it must return to the same initial value during the next cycle. In terms of electric voltage, the area under the voltage function generated by a cone 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 essentially linear over the entire output range and third the output current was substantially the same for variations in input voltage. Voltage, frequency

MR. R. A. RAYMER, for the production of reports  
Amplifier Operation, Naval Research Laboratory  
Number 2739, United States Department of Defense,  
Washington 25, District of Columbia, January 22, 1952.

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and modifications have appeared on Ramey's circuit.<sup>23, 24, 25</sup>

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.<sup>26</sup>

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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<sup>23</sup> C. B. House, "Flux Preset High Speed Magnetic Amplifiers," Communication and Electronics, 10:728-735, 1954.

<sup>24</sup> D. G. Scorgie, "Fast Response with Magnetic Amplifiers," Communication and Electronics, 10:741-749, 1954.

<sup>25</sup> R. L. Van Allen, "A Magnetic Amplifier for Synchronos," Communication and Electronics, 10:749-757, 1954.

<sup>26</sup> 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 resulted in a more efficient design.

Properties and Design of the Amplifier

The properties of the magnetic material used in the amplifier play an important part in the design of the amplifier. The physical constants of the core material are equally important parts in amplifier design. The following information on the properties of the magnetic material is taken from the manufacturer's Bulletin.

To take full advantage of the high permeability of Belmar, a certain type of core construction is suggested. It is well known that with magnetic material having a relative 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 permeability to about 100. In the design of a core, the length of magnetic path is usually chosen so that this same circuit would reduce permeability to the inches the effective permeability would be increased to a value of about 100. The permeability of Belmar is generally between 100,000 and 200,000, and also varies with frequency. The minimum

It has been common practice to use magnetic materials of the general type for those applications where 0.005 inch or thicker material was desired.

23 D. E. House, "The Design of Magnetic Amplifiers," Communication and Electronics, Vol. 1, No. 1, 1954.

24 D. G. Scobie, "The Design of Magnetic Amplifiers," Communication and Electronics, Vol. 1, No. 1, 1954.

25 R. L. Van Allen, "The Design of Magnetic Amplifiers," Communication and Electronics, Vol. 1, No. 1, 1954.

26 The Arden Engineering Company, Design of Magnetic Amplifiers, Bulletin TO-101A, Properties of Belmar, 4-13-54, and Supplement, pp. 1-4, 15 March 1954.



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. . . .

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.<sup>27</sup> 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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<sup>27</sup> J. E. Mitch, "Material Properties and Specification of Magnetic Amplifier Cores," paper presented before the Los Angeles Section Meeting, AIEE on January 12, 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.<sup>28</sup>

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'.<sup>29</sup> While the load current can be reduced smoothly from its maximum value by adjustment of the control current, once

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<sup>28</sup> 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.

<sup>29</sup> Ibid., pp. 223-228.



to heat treatment. Recombination of a core material may be judged by several factors, among them being the ratio of recombination to recombination rate, the ratio of recombination to recombination rate, and the ratio of recombination to recombination rate. The ratio of recombination to recombination rate will vary by a factor of 10 or more, depending on being affected by metallurgical processes, such as treatment, eddy currents, and core geometry. The ratio of losses depend on material properties, recombination rate, maximum rate of change of flux density, and the ratio of core with a low ratio of core material to the diameter will have a greater differential recombination rate, as a larger ratio of recombination to peak induction.

Although recombination is usually neglected in higher efficiency and high-frequency designs, it may be of back worth of noise, heating and distortion. Rejection is instability noted in magnetic amplifiers using recombination core material, some times referred to as "core noise". While the load current can be reduced slightly for the maximum value by adjustment of the control current, does

As discussed by D. C. Johnson in "Magnetic Amplifiers" and W. N. Johnson, "The Design of Magnetic Amplifiers" in the Journal of the IRE, Communication and Electronics, Vol. 1, No. 1, 1953.



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.<sup>30</sup> 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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<sup>30</sup> 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.



having reached minimum value, the low current range as  
increased again slightly but was inhibited by a rather  
large value, before the normal wanted quantity was  
resumed. They were able to reduce this effect in some  
certain type materials.

With all of the variables that may be introduced  
into the magnetic properties of some materials, the need  
of means of evaluating the characteristics of the  
product is apparent. Much and other have presented a  
summary of techniques employed in production testing of  
tape wound magnetic materials. The electrical method  
the sine flux and sine current methods, which compare  
their chief difference lies in the source of the  
exciting current, is being high in the case of the  
for sine flux. In both methods, the exciting current is  
fed through a low resistance shunt to a magnetic winding  
on the core under test. A galvanometer then reads the  
induced voltage through an impedance to the vertical  
plates of an oscilloscope, and the voltage across the  
shunt (proportional to exciting current) is also indicated  
force) is fed to the horizontal plates. The resulting  
diagrams figures represent the hysteresis loop of the

To J. E. Mitchell, Jr., Los Angeles, California  
Production Testing of Tape Wound Magnetic Materials  
sent at AIEE Summer and Fall Conventions, Los Angeles,  
California, 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.<sup>31</sup> 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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<sup>31</sup> H. W. Lord, "Dynamic Hysteresis Loop Measuring Equipment," Communication and Electronics, 2:269-272, 1952.



core under test. The same film method is used to measure  
 to distortions in the regions of the test. The film is  
 to stray polarization resulting from the distortion of the  
 existing current occurring in the various circuit elements.  
 A testing method is proposed which will identify elements  
 the operation of the core in a half-wave self-resonance  
 circuit. This test consists of determining the average  
 output voltage, or flux change, as a function of the  
 reset magnetizing force for a given value of half-wave  
 wave magnetizing force, plotted on a graph of the  
 transfer characteristics. Using the test method described  
 above, basic core properties can be determined within limits  
 of 5 to 10 per cent, and the degree of accuracy obtained  
 by the constant current method is comparable with  
 that obtained by other methods.

Problems encountered in the display of waveforms  
 of dynamic hysteretic loops are discussed by J. W. Lord,  
 on an arbitrary error of 5 per cent error in indicated  
 values, no derived data allowing minimum performance char-  
 acteristics of the amplifier in the vertical and horizontal  
 deflection circuits. For a three stage amplifier in the  
 horizontal circuit, each stage would have a phase shift of  
 less than 45 degrees at 100 cycles per second. This is not less



250 times the supply frequency. Each stage of a three stage amplifier in the vertical deflection circuit must have less than 45 degrees phase shift at one three hundredth the exciting frequency and at one hundred times the exciting frequency. The requirements for low frequency response of the vertical amplifier are considerably less severe if suitable compensation is made in the integrating network.

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.<sup>32, 33</sup> 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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<sup>32</sup> Lehmann, op. cit., p. 2099.

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







looked, and believed this factor to be the proper consideration of the effects of eddy currents. Although eddy current effects can be reduced by using thinner laminations, their presence can be detected in even the thinnest materials at the lowest time rates of change of flux, and these effects cannot be accounted for by skin effect.<sup>34</sup> He presents data in support of the contention that a broader (greater H) hysteresis loop is obtained for the same flux change with the same core if the time rate of change of flux is increased. If the increase is provided by a constant current source, the sides of the hysteresis loop are vertical, indicating an apparent infinite differential permeability. The effects of eddy currents are indicated by the reset mechanism of the half-wave self-saturable circuit, in which the control winding current is held constant by its high source impedance, and current flow in the gate winding is prevented during the reset cycle, yet the flux may be changed from positive to negative saturation.

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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<sup>34</sup> H. W. Lord, "Dynamic Hysteresis Loops of Several Core Materials Employed in Magnetic Amplifiers," AIEE Transactions, 72:85-88, Part I, 1953.



looked, and believed this to be the correct direction  
of the effect of edge currents. It is generally  
current effects can be reduced to the minimum by  
their presence can be neglected as even the smallest  
at the lowest rate of change of flux, and these  
effects cannot be accounted for by skin effect. The  
same data in support of the conventional case is  
(Grapher B) hysteresis loop is obtained for a  
change with the same rate of change of flux  
flux is increased. If the frequency is varied by a  
stant current source, the slope of the hysteresis loop  
vertical, indicating an absence of hysteresis  
permeability. The effects of edge currents are  
by the reed mechanism of the half-wave-rectifier  
circuit, in which the current which circulates  
constant by its high current density, and constant  
the gate winding is prevented during the reverse  
the flux may be changed from positive to negative  
While Lord discussed a mechanism to change the  
for some of the characteristics shown in theory and  
Hunt plotted some of the actual waveforms showing  
core being reset from saturation by means of a constant



magnetizing force.<sup>35</sup> Results are plotted for several thicknesses of four types of core materials commonly used in magnetic amplifier design. With a constant current sufficient to cause saturation applied through one of the three windings on the test cores, a pulse of sufficient amplitude to cancel the effect of the bias and cause saturation in the opposite direction was applied. At the end of this pulse, the voltage across a monitoring winding was observed on an oscilloscope. This study is valuable in that it shows the irregular nature of the voltage (and hence the time rate of change of flux) resulting during constant current reset. The resetting magnetizing force was adjusted for each test so as to complete reset in a fixed time of about 0.010 seconds. It is felt that considerable value would accrue from a plot showing the time required for reset from positive to negative saturation for a particular configuration and for several values of magnetizing force.<sup>36</sup>

Limitations of the Literature. It appears that considerable effort has been expended in attempting to use the hysteresis loop as a basis for magnetic amplifier design. Inasmuch as many efforts have shown poor correlation between

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<sup>35</sup> H. Huhta, "Flux Resetting Characteristics of Several Magnetic Materials," Communication and Electronics, 12:111-114, 1954.

<sup>36</sup> Cf. post, p. 45.



magnetizing force. The results are plotted for several thicknesses of lens system of one wavelength. It is seen that in magnetic amplifier design, with a constant current, sufficient to cause saturation, the voltage across one of the three windings on the test core, a glass core, is sufficient amplitude to cancel the effect of the bias and counteract action in the opposite direction was applied. At the end of this pulse, the voltage across a saturating winding was observed on an oscilloscope. This voltage is shown in that it shows the irregular nature of the voltage (and hence the time rate of change of flux) resulting during the transient current pulse. The resulting magnetizing force was adjusted for each test so as to compare with a fixed value of about 0.010 seconds. It is felt that considerable values would accrue from a plot showing the time required for reset from positive to negative saturation for a particular configuration and for several values of magnetizing force.

Limitations of the Experiment. It is felt that considerable effort has been expended in attempting to see the hysteresis loop as a data for a magnetic amplifier. Inasmuch as many effects have not been included, however,

J. R. Hulse, "The Magnetic Amplifier,"  
Several Magnetic Amplifier Circuits for the Navy,  
NS-111-111, 1954.



actual and predicted results, especially for the case of the half-wave circuit, it appears that some other design basis should be investigated.

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;<sup>37</sup> (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;<sup>38</sup> (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;<sup>39</sup> (4) the magnetizing current flowing during the gating cycle may be neglected when calculating the firing angle;<sup>40</sup> (5) core materials are available in which the saturation flux and the remanent flux are approximately equal.<sup>41</sup>

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<sup>37</sup> Dornhoefer, op. cit., p. 845.

<sup>38</sup> Ramey, op. cit., p. 23.

<sup>39</sup> Huhta, op. cit., p. 114.

<sup>40</sup> Dornhoefer, op. cit., p. 844.

<sup>41</sup> The Arnold Engineering Company, op. cit., p. 6.



actual and predicted results, especially for the case of the half-wave circuit, it appears that some other basis data should be investigated.

Summary. The following information regarding 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 firing cycle to the saturated value. (2) The average output voltage-time function occurring during the firing cycle is a measure of the initial flux available at the beginning of the next firing cycle. (3) The average output voltage available for reset at any instant during the firing cycle cannot exceed the supply voltage by an amount greater than that which and rectifier drop. (4) The average output voltage during the firing cycle may be maintained constant if the firing angle is constant and the average flux available which the saturation flux and the average flux are approximately equal.

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37 Dornhoefer, op. cit., p. 11.  
38 Harvey, op. cit., p. 23.  
39 Hines, op. cit., p. 14.  
40 Dornhoefer, op. cit., p. 11.  
41 The Arnold Engineering Company, St. Louis, Mo.



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;<sup>42, 43</sup> (7) hysteresis loops are affected by a great number of factors;<sup>44</sup> (8) severe requirements must be met by equipment used to measure dynamic hysteresis loops;<sup>45</sup> and (9) when reset from saturation only by the action of a constant magnetizing force, irregular waveforms appear across the gate windings.<sup>46</sup>

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<sup>42</sup> Lehmann, op. cit., p. 2101.

<sup>43</sup> Storm, op. cit., p. 640.

<sup>44</sup> Gf. ante, p. 17 et sqq.

<sup>45</sup> Lord, "Dynamic Hysteresis Loop Measuring Equipment," op. cit., p. 271.

<sup>46</sup> Huhta, op. cit., p. 113.



Other results noted are: (1) the function of the control magnetizing force on results in the case of some material in between the static and dynamic hysteresis loops of the core material involved; (2) the function of the control magnetizing force on results in the case of some material are affected by a great number of factors; (3) the requirements must be met by any test used to measure dynamic hysteresis loops; (4) and (5) that waves from a certain action only by the action of a constant magnetizing force, irregular waveforms appear across the core material.

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- 42. Latham, W. C., p. 110.
  - 43. Storm, W. H., p. 110.
  - 44. G. L. Guss, p. 110.
  - 45. Lord, W. P., p. 110.
  - 46. Hints, W. C., p. 110.



## 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,<sup>1</sup> 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.<sup>2</sup> 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.<sup>3</sup> Inasmuch as it would be quite unreasonable to expect the manufacturer of core material to

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<sup>1</sup> W. J. Dornhoefer, "Self-Saturation in Magnetic Amplifiers," AIEE Transactions, 68:837, Part II, 1949.

<sup>2</sup> 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.

<sup>3</sup> Henry Lehmann, "Predetermination of Control Characteristics of Half-Wave Self-Saturable Magnetic Amplifiers," AIEE Transactions, 70:2102, Part II, 1951.



METHOD AND APPARATUS

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 control cycle, and that a measure of this flux is the voltage induced in the voltage appearing across a winding of the core during the previous reset cycle. In the half-wave self-excitation circuit, the degree of flux reset is determined by the amount of constant magnetizing force applied to the core via the control winding. The degree of reset is also related with the problem of determining an effective number of turns of control winding. Where necessary to achieve the degree of control required, hereafter, this information was obtained from a hydraulic loop of the core at the frequency desired. Inasmuch as it would be unreasonable to expect the manufacturer of core material to

1. W. J. Dornberger, "Magnetic Amplifier Characteristics," IEEE Transactions, Vol. 67, Part II, No. 1, 1958.

2. R. A. Egan, "On the Mechanism of Magnetic Amplifier Operation," IEEE Transactions, Vol. 67, Part II, No. 1, 1958.

3. Henry Johnson, "Characteristics of Magnetic Amplifiers," IEEE Transactions, Vol. 67, Part II, No. 1, 1958.



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,<sup>4</sup> 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.<sup>5</sup> A finite time, however is required for this change of state to take place.

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<sup>4</sup> H. W. Lord, "Dynamic Hysteresis Loop Measuring Equipment," Communication and Electronics, 2:269-272, 1952.

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

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, 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 26 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. A finite time, however, is required for this change of state to take place.

H. W. Lord, "Dynamic Hysteresis Loop Measuring Equipment," Communication and Electronics, 2:269-272, 1951.

Reproduced with permission from The Arnold Engineering Company, Marenco, Illinois, Bulletin TC-101-A, Properties of Delimax, 4-79 Mc Ferralloy, and Super-Malloy, page 10, 15 March 1953, Reprinted January 1956.



# DELTAMAX

Specimen Core  
4168-D-2

$\mu_r = 560$

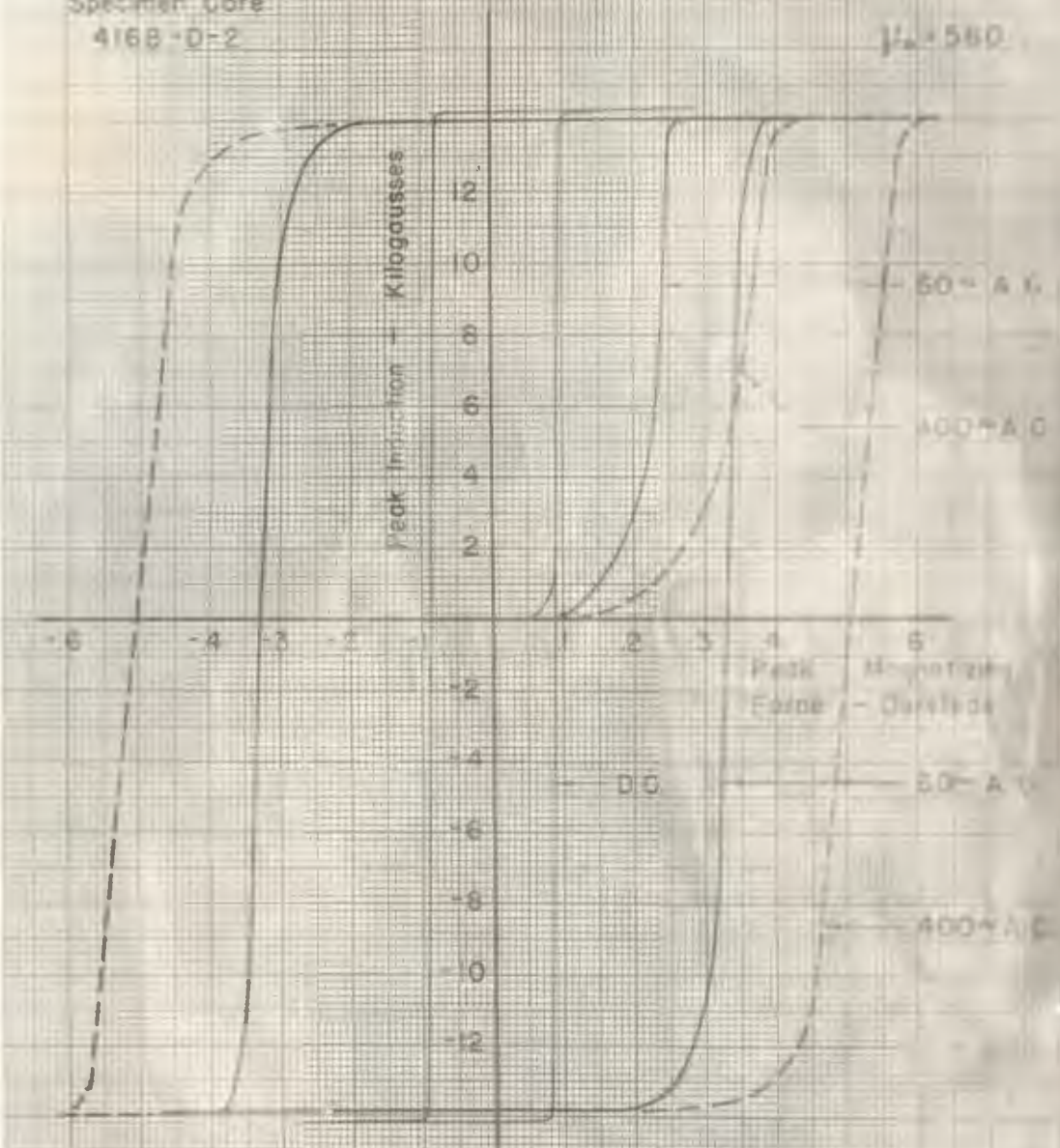


FIG 1 D.C. AND A.C. MAGNETIZATION CURVES  
AND HYSTERESIS LOOPS  
OF DELTAMAX





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.



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

If sufficient magnetizing force is applied to the core to reverse magnetization in one half cycle of the supply frequency, the core will not return to its preceding magnetizing cycle, a further flux change will not properly designed.

Therefore, a limit is placed on the magnetizing force and resulting flux change to prevent the core from reversing to negative magnetization in the reverse half cycle of the supply frequency. The designer of the magnetic amplifier must design the circuit to meet the following criteria.

An additional factor, however, must be considered. During the next cycle the power supply voltage is normally prevented from acting on the core by the action of the rectifier. However, if the value of  $R_L$  due to the structure of the current magnetizing force causes a voltage across the winding that exceeds the instantaneous supply voltage, the rectifier will conduct. This results in the supply voltage being applied across the winding, and the flux change 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.<sup>6</sup> 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.<sup>7</sup>

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

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



To study these phenomena, the test specimens for a magnetic amplifier were studied both for the case of rest alone, and in the presence of an applied alternating current. In addition, a plot of the test current versus values of magnetizing force was made.

## II. EQUIPMENT USED TO OBTAIN DATA

Magnetic amplifier. The magnetic amplifier was wound on a Delemax 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. Especially noteworthy are the reverse current characteristics. In order to avoid this care was exercised in the selection of the rectifier whose properties are listed in Table III. To further insure the availability of this device, the manufacturer's manual is principally as a replacement for ordinary rectifiers on the low voltage power supplies in case of an emergency.

W. H. P. Stern, "Theory of Rectifier Amplifiers and Square-Loop Core Materials," Communication and Electronics, 9:636, 1958.

Y. Sakas-Tarjan, "Investigation of Rectifier Amplifiers," Bloomington, Indiana, Army Research Office-Durham, Procedure Using Sakas-Tarjan Rectifier Amplifier, 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 . . . . .	$3.000\pi$ inches
Saturation flux density . . . . .	14,000 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 milliamper control current	
calculated . . . . .	0.0284 oersteds per milliamper

EXHIBIT  
CORRASABINE  
7-1-1902

Static capacity factor . . . . . 0.05  
Saturation flux . . . . . 0.01  
Saturation factor . . . . . 0.01  
Saturation flux density . . . . . 0.01  
Mean path length of flux . . . . . 0.01  
Gross section width . . . . . 0.01  
This case . . . . . 0.01  
Outside diameter . . . . . 0.01  
Inside diameter . . . . . 0.01  
Tape thickness . . . . . 0.01  
Number of turns . . . . . 0.01  
Core material . . . . . 0.01

TABLE II

REPORTING ON RESULTS

Gate winding . . . . . 500 turns  
Control winding . . . . . 500 turns  
Peak induced voltage . . . . .  
by gate winding as shown  
calculated . . . . .  
measured . . . . .  
Control magnetizing current  
milliamperes control current  
calculated . . . . .

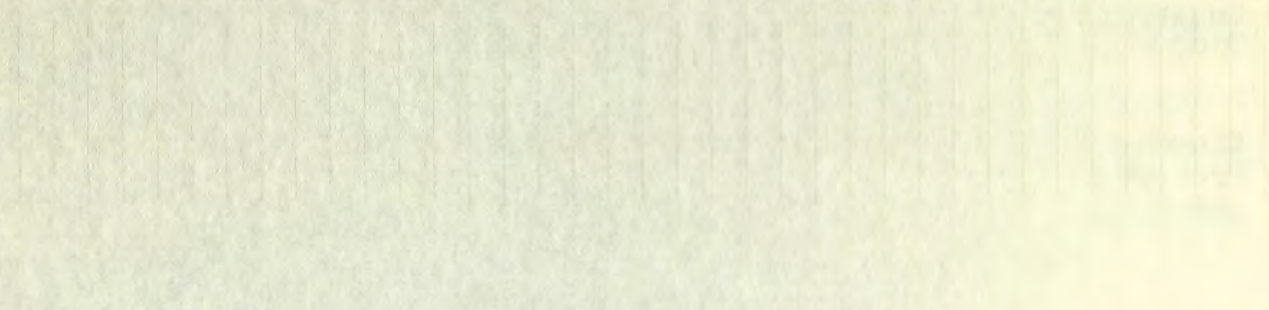




TABLE III.

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



100

TABLE III

PROPERTIES OF RESISTOR TAP

Type	100 ohms (1/2 W)
Manufacturer and type	GenCorp-Tektron, 2-50
Peak inverse voltage (rated)	50 volts
Forward voltage drop (average)	0.15 volts
at 50 milliamperes	0.15 volts
at 100 milliamperes	0.15 volts
Reverse current (average)	0.15 microamperes
at 50 volts	0.15 microamperes
at 100 volts	0.15 microamperes
at 200 volts	0.15 microamperes

4474  
REV  
BOND



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.



Constant current device. A constant current device was provided by connecting the control circuit to the plate circuit of a type 6X4 vacuum tube whose bias was varied by a potentiometer in the cathode, and whose screen voltage was stabilized at 150 volts.

Saturating device. To obtain the required saturation the core was saturated in the positive direction by application of a direct current through the grid winding. This current flowed through the plate circuit of a type 6X4 vacuum tube. Provision was made for the sharp cutoff of this plate current by application of approximately 500 volts negative bias to the grid. An application of this bias, a negative trigger pulse was fed to the sweep circuit of an oscilloscope.

Instrumentation. Oscilloscopes were used for the Tektronix model 555 oscilloscope whose bandwidth is 10 megacycles and whose input impedance exceeded 10 megohms, according to manufacturer's specifications. Its utilization sensitivity was calibrated against a Weston model 510 dynamometer voltmeter whose rated sensitivity was one half per cent, and found to be twenty-five and two thirds volts per centimeter on the scaling used. Current measurements were made with a sensitive inductance type Rogowski coil, standard meter whose rated accuracy was one percent 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

Magnetic Amplifier Waveforms. Waveforms are shown

waveforms were plotted using the circuit shown in Figure 2, page 35. The oscilloscope was powered so that the voltage across the gate winding during the positive half of the cycle line voltage, with the gate voltage amplified by the same voltage. Waveforms were taken with values of control magnetizing force corresponding approximately to the angles of forty-five, ninety, one hundred thirty-five and one hundred eighty degrees.

Reset Waveforms. Waveforms are shown in Figure 3.

were obtained with the circuit shown in Figure 3, page 36. The current through the gate winding was adjusted to a value that would produce a repulsive force of approximately one oersted, sufficient for accurate, so adjusted, to oppose the control magnetizing force. With the control current adjusted to the value for which the repulsive force was approximately two hundred volt-ampere lines per inch through a Rogowski pickup, the induced voltage of the coil, exciting off the gate winding circuit. The gate voltage was illustrated in the figure. The gate voltage was on the oscilloscope. The gate of the tube was also on the oscilloscope. The first was obtained by means of a probe connected to the actual reset waveform, measured with one of the gates of



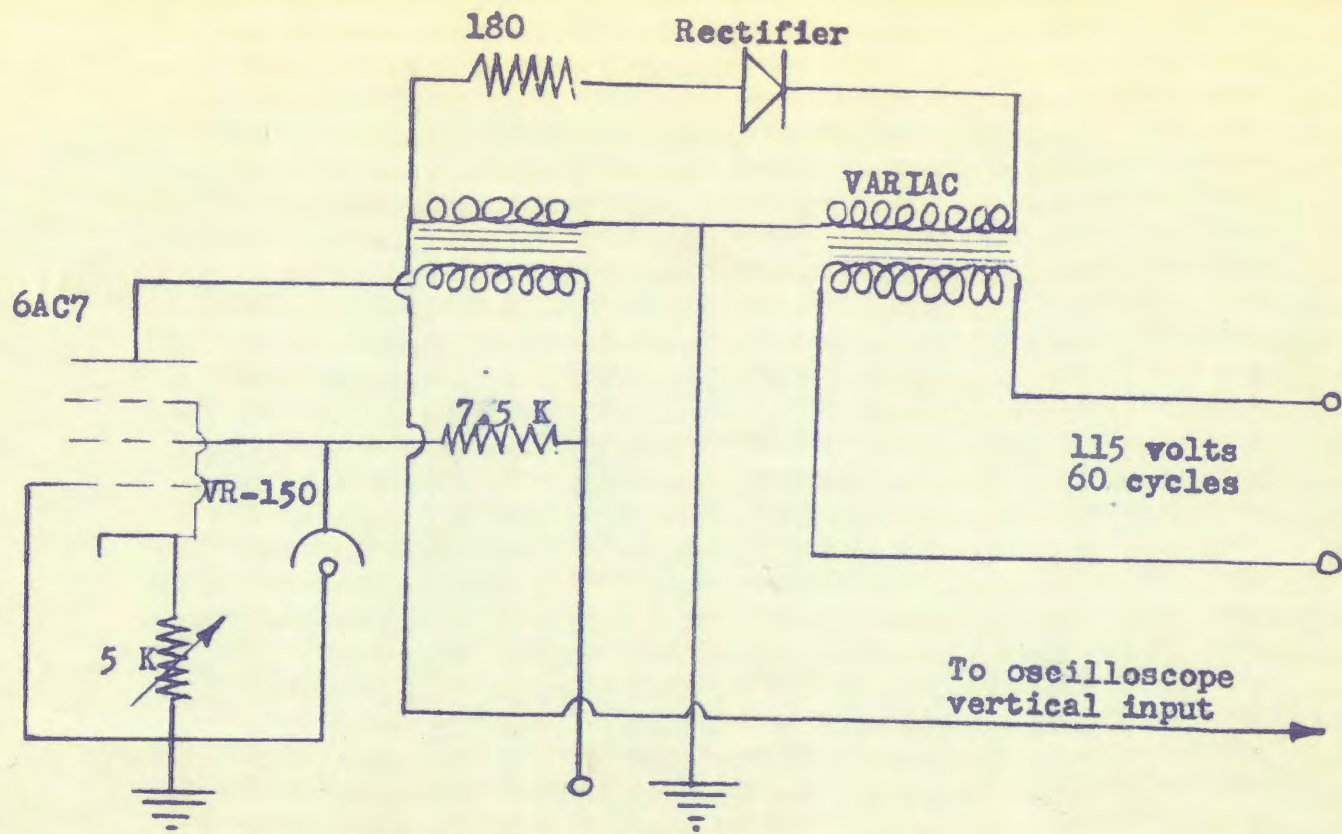


FIGURE 2

CIRCUIT USED TO DETERMINE  
MAGNETIC AMPLIFIER WAVEFORMS

Example of a circuit diagram





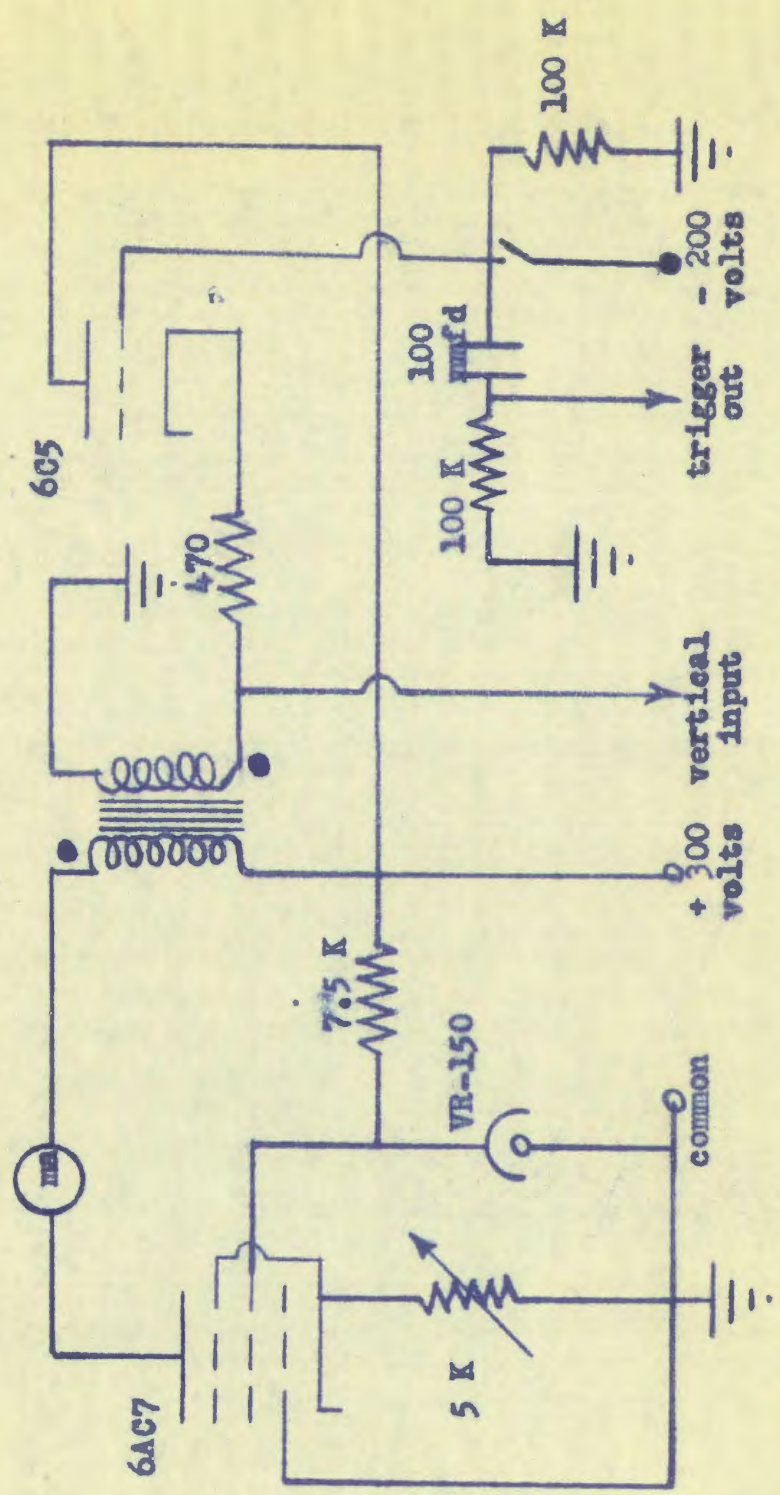


FIGURE 3  
CIRCUIT USED TO DETERMINE  
RESET FUNCTIONS

UNIVERSITY OF MARYLAND  
COLLEGE PARK, MARYLAND

LABORATORY





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.<sup>8</sup> Past this point, the control current was reduced in increments of one half milliamperes until three successive settings resulted in the same output current.

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<sup>8</sup> 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.



control current used to obtain the magnetic field wave-  
forms described in a previous section above. For wave-  
forms, the horizontal deflection was adjusted so that  
millisecond per centimeter, giving a total sweep width of  
ten milliseconds, or slightly more than one full cycle of  
sixty cycles per second. The second set of curves was taken  
to determine the time for complete reset to zero after the  
function of applied magnetizing force. The vertical def-  
lection of the oscillations was adjusted so that the reset  
function intersected the zero axis at a sharp angle.

Transfer characteristics. The transfer characteristics  
was plotted using the circuit of Figure 4, page 25. Control  
current was adjusted by varying the bias on the control  
current tube. The maximum control current was that  
which just reduced the output current to the minimum value.  
The control current was reduced until the output current  
described by Barbour and Johnson was noted. The output  
the control current was reduced in increments of one half  
milliamperes until three successive zero current values in the  
same output current.



## 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.<sup>9</sup> 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

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<sup>9</sup> Storm, op. cit., pp. 632-634.



#### IV. CALIBRATION DATA

An approximate transfer characteristic was obtained by determining its end points from the known values of coercive force and the experimentally determined remanent force necessary to reset the core to magnetic saturation in one half cycle.

#### Total circuit resistance. The power-supply no-load

voltage was measured open circuit and the amplifier connected and adjusted for a phase angle of two degrees, the average load current was measured, the total circuit resistance was assumed to be the ratio of voltage divided by twice the total load current (including the entire quantity divided by two for the current). This procedure was employed because no direct current meters of sufficient accuracy were available.

#### Transfer characteristics. No attempt was made to

determine accurately the shape of the transfer characteristic, as this has been done elsewhere. Only the extreme value of control magnetic flux was used to determine output and that resulting in maximum output was selected. In other words, the transfer characteristic was assumed to be its proper position with relation to the magnetic



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 1, page 20, shows that a constant  
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 a direction in the opposite  
direction, provided sufficient time is allowed. Therefore,  
the maximum value of magnetizing force can be determined in  
maximum output will be taken as the maximum positive  
force of the core material.

Reference to Figure 1, page 20, shows that the flux  
will be changed from positive to negative saturation in a  
time determined by the amount of current magnetizing force  
applied. Any value of coercive magnetizing force in excess  
of that required to reach the positive 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, that is, that  
which produces magnetizing forces between the static  
coercive force and the magnetizing force that causes 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.



## V. ASSUMPTIONS

Assumptions implicit in the methods used here are

listed in the following paragraphs.

Volts drops. The load impedance is assumed resistive and lumped in the load resistance. The voltage is assumed to have a constant forward voltage drop which is independent of load current, the cathode-ray tubes are constant.

Magnetic properties of core material. The magnetic

coercive force, saturation flux density, and permeability factor are assumed to have the values indicated by the manufacturer. The permeability of the core material in the saturation region is assumed infinite.

Power supply. The alternating current power supply

used was the sixty cycle power line. The voltage was monitored during all tests to insure the constant voltage within one half per cent, and the frequency was assumed to be sixty cycles per second to within one per cent.

Measurements. All measurements were assumed to be

within the accuracy stated on their name plates. Laboratory standard meters calibrated within three months before 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

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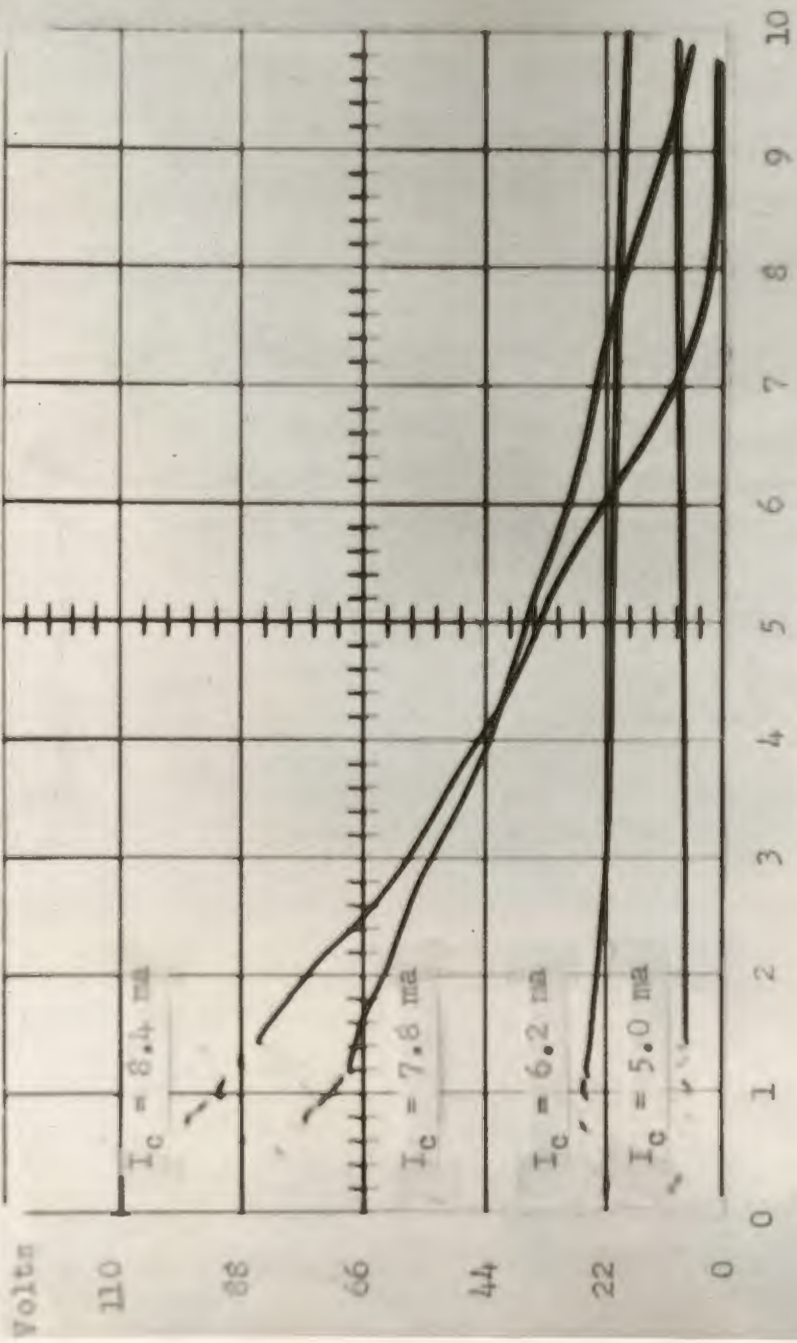


FIGURE 4  
RESET FUNCTIONS FOR  
SEVERAL VALUES OF MAGNETIZING FORCE





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

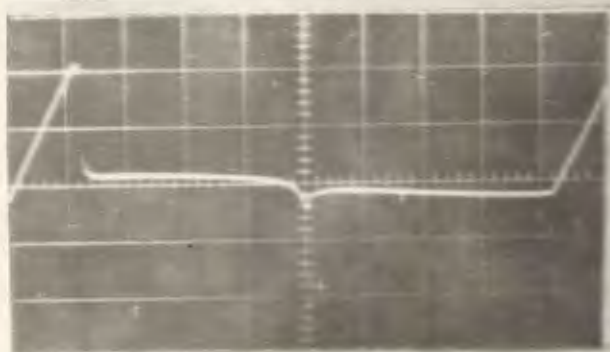
Transfer characteristic. The transfer function was plotted as load current versus control current. Control current corresponding to the static coercive force of the core material was indicated for reference. Likewise, the control current producing reset from positive to negative saturation in one half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

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.





144  
FIGURE 5  
GATE WINDING WAVEFORM  
 $I_c = 5.0$  ma  
 $E_{pk} = 48$  volts



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

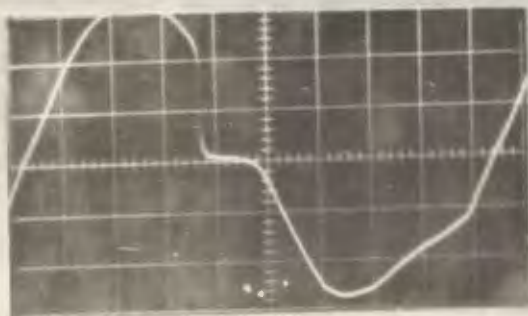


FIGURE 7  
GATE WINDING WAVEFORM  
 $I_c = 7.8$  ma  
 $E_{pk} = 71$  volts

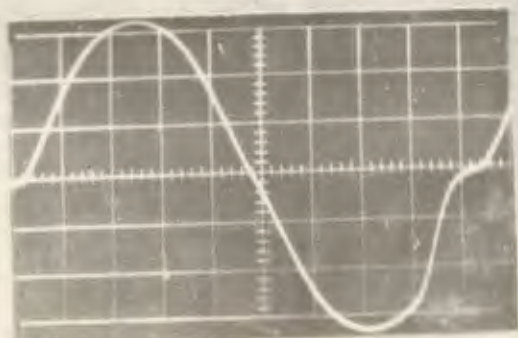


FIGURE 8  
GATE WINDING WAVEFORM  
 $I_c = 8.4$  ma  
 $E_{pk} = 71$  volts





Control current  
milliamperes

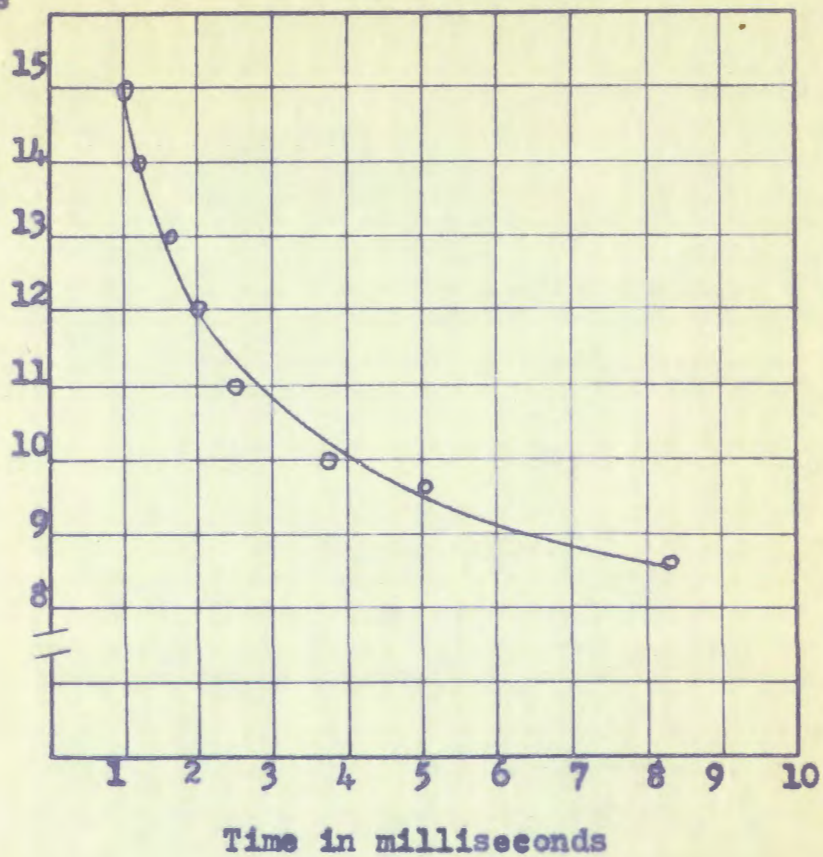
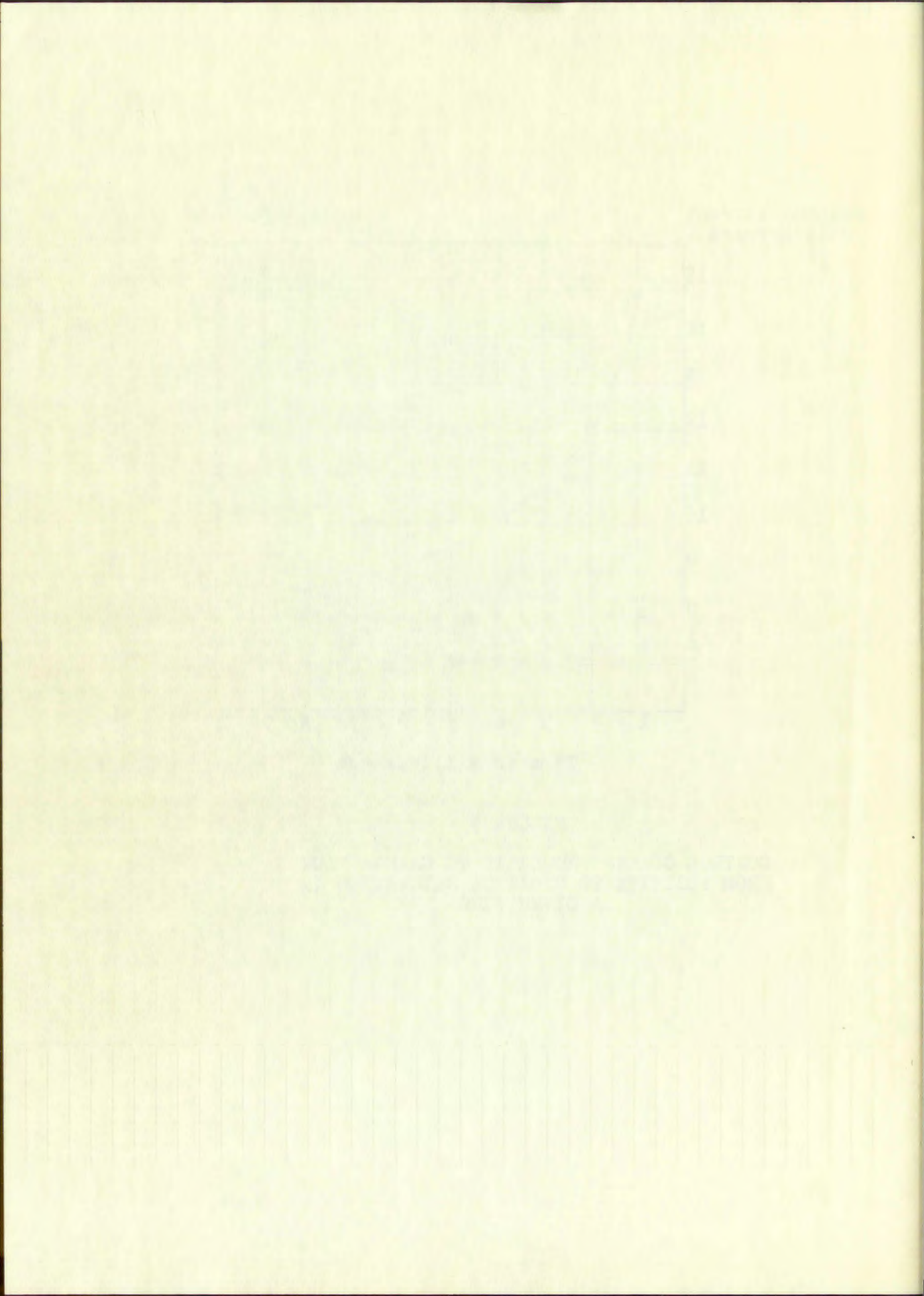


FIGURE 9

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





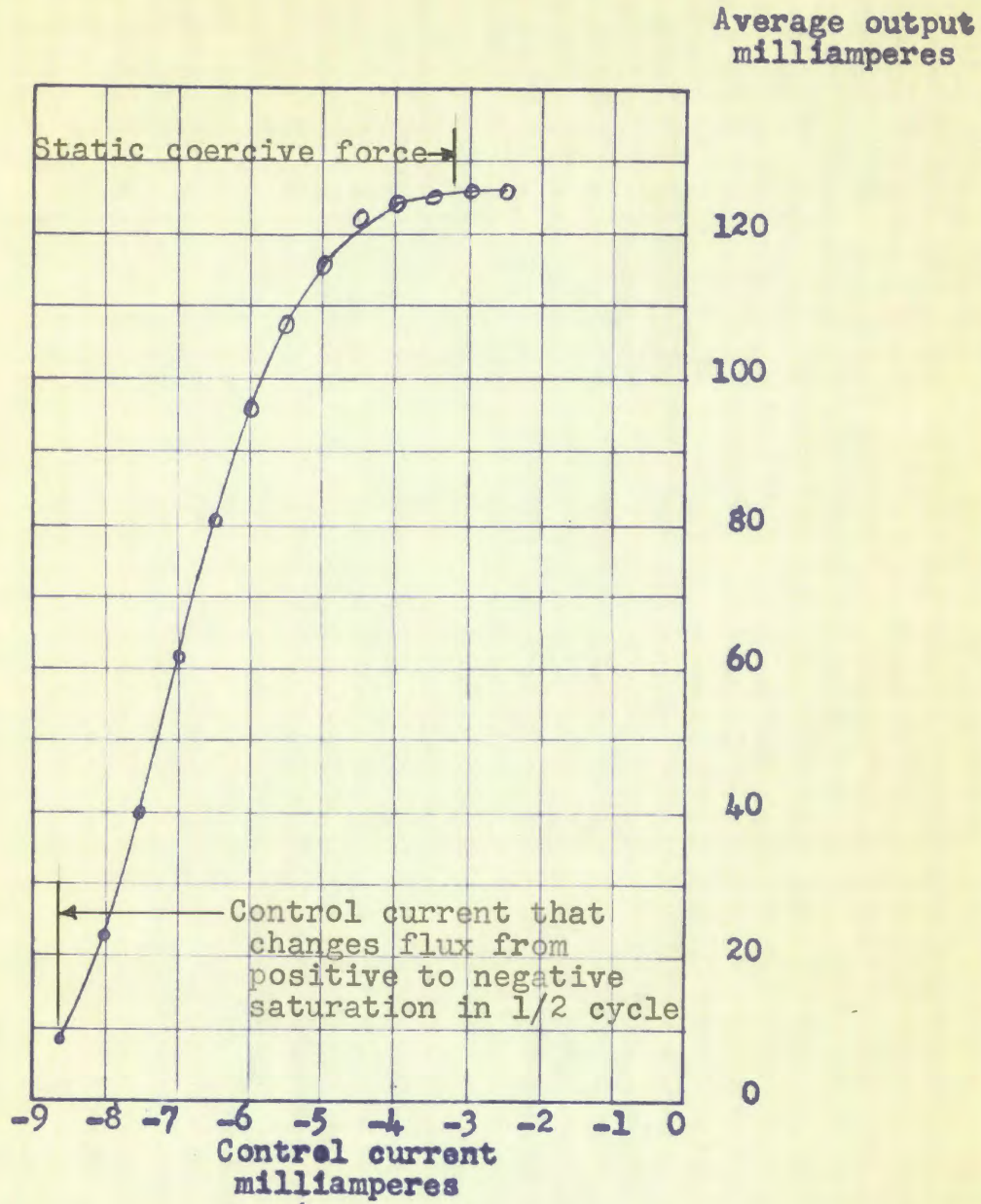


FIGURE 10  
TRANSFER CHARACTERISTIC

Figure 1  
 Average  
 ...



Figure 1  
 Average  
 ...



## 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



CONCLUSIONS

Conclusions reached from the study are: (1) the circuit as tested by constant current to a degree which is the amplitude and frequency of the alternating current supply; and (2) a plot of the time required for the negative saturation from positive saturation at a constant of constant magnetizing force which is in line with the origin of magnetic amplifiers. This plot, along with the static coercive force, would place the core and position of the transfer characteristics in their proper relation to the origin of the B-H function of the core material.

1. CIRCUIT OPERATION

A given amount of current through all inductance resultant change during the pulse cycle. The flux density in the core at the beginning of the following pulse cycle determines the firing angle, and hence, the average current delivered to the load during this pulse cycle. Attention is invited to the fact that the average value of flux is approximately constant. Comparison with the waveform produced during the pulse cycle of the amplifier, Figures 5 and 6, page 4, show waveforms



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.<sup>1</sup> 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

---

<sup>1</sup> 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.



BOARD  
RESOLUTIONS

having the same shape and width, and the same length  
exception: a sharp increase in the rate of change  
change in slope occurs at the end of the first cycle.  
This latter portion of the reset function is especially  
voltage. Since the voltage is constant, the rate of  
the supply voltage at the time of the first  
simply, the resulting flux is constant and the  
that it connects, applying the same voltage to the  
gate winding. The flux in the core is determined at a rate  
determined by the supply voltage, which is the same as  
as the Ramey circuit, changing at zero frequency, so  
when the supply voltage reaches zero, the rate of  
stant magnetizing force has been applied, the rate of  
supply voltage used, the supply voltage would be  
below the reset function at an earlier time. The  
under the reset function and hence the rate of change during  
the reset cycle, would have been the same. However,  
a higher magnetizing force would have been necessary to  
produce the same flux change in the same time interval  
by the higher frequency.

With the higher values of flux, the rate of change  
in figures 7 and 8, page 4, the reset function is shown  
I. R. Ramey, 4101 the University of Colorado  
After Operation, 11, 1954, University of Colorado  
3733, United States Department of Commerce, Bureau of  
District of Columbia, January 22, 1954.



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 milliamperere 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.<sup>2</sup> Therefore the simple "gating" process described above for the case of small firing angles does not appear to correlate

---

<sup>2</sup> H. Huhta, "Flux Resetting Characteristics of Several Magnetic Materials," Communication and Electronics, 12:113, 1954.

be introduced during the first part of the process.  
Reference to corresponding curves in Figure 1 shows that  
initially the current is very low and increases rapidly  
value. The induction is due to the reaction between  
during this interval and the supply voltage are applied  
across the gate winding. A characteristic curve is  
approximately two hundred seventy volts in Figure 1,  
followed by a voltage of an inductor lamp, and this  
near the end of the process cycle, the supply voltage takes  
control. Figure 2 exhibits a sharp discontinuity, and  
the "trailing edge" of the wave, which is clearly  
introduced, exhibiting such a high frequency of the  
B.A. milliamperes curve in Figure 3, as is shown in  
rate of change.

The second mode of operation is used to amplify the  
prediction as that noted for small to intermediate values  
of firing angles. It has been shown in the circuit diagram  
constant current reactor function and is shown in Figure 4.  
ditions other than saturation, the current is shown in  
these obtained when the gate is initially opened. It is  
fore the simple "gate" method of operation, and in the  
case of small firing angles does not appear to be

J. H. ...  
Several ...  
12-13, 1934.



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.<sup>3</sup> 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.<sup>4</sup>

Arguments stating the role of the static hysteresis loops in magnetic amplifier design have been previously presented.<sup>5</sup>

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

---

<sup>3</sup> H. F. Storm, "Theory of Magnetic Amplifiers with Square-Loop Core Materials," Communication and Electronics, 9:643, 1953.

<sup>4</sup> Cf. ante, p. 4.

<sup>5</sup> Cf. ante, p. 39.



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MAY 1953

too well with the constant current source. A similar process is also observed in the case of...

### II. THEORY

The shape of the constant current source was described by Strom. However, the relation to the static hysteresis loop was not considered. It is shown in this paper that the width of the dynamic hysteresis loop is a function of the supply frequency. Theoretical considerations in obtaining dynamic hysteresis loops for non-linear power supply frequencies have been previously stated. Arguments stating the role of the static hysteresis loop in magnetic amplifier design have been previously presented.

The same magnetizing force when applied in a certain angle of one hundred eighty degrees in the magnetic amplifier also changed the flux in the same direction. In negative saturation in a time equal to the half cycle of the steady cycle power supply frequency, the hysteresis loop core was available for each, this condition was also...

J. H. P. Strom, Theory of Magnetic Amplifiers, Square-Loop Core Materials, Proceedings of the IRE, 41: 1053, 1953.

1. G. L. ...  
2. G. L. ...

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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 occurring between the constant current waveforms of Figure 4 and the sinusoidal supply voltage.



close to be the result of... of core materials could... core a curve similar to... static cohesive force... local information... frequencies and... this range of control...

III. LIMITATIONS AND CONCLUSIONS

It is acknowledged that... presented to compare... force required to change... tive to negative... cycle will always be... angle of one hundred... at that frequency... obtained for one case... results, appear to...

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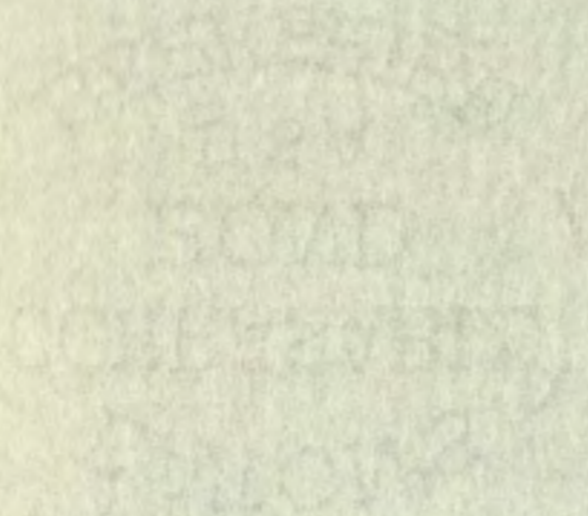
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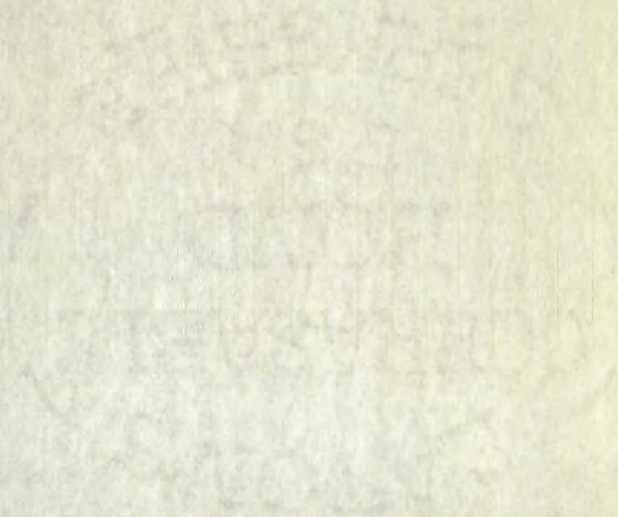
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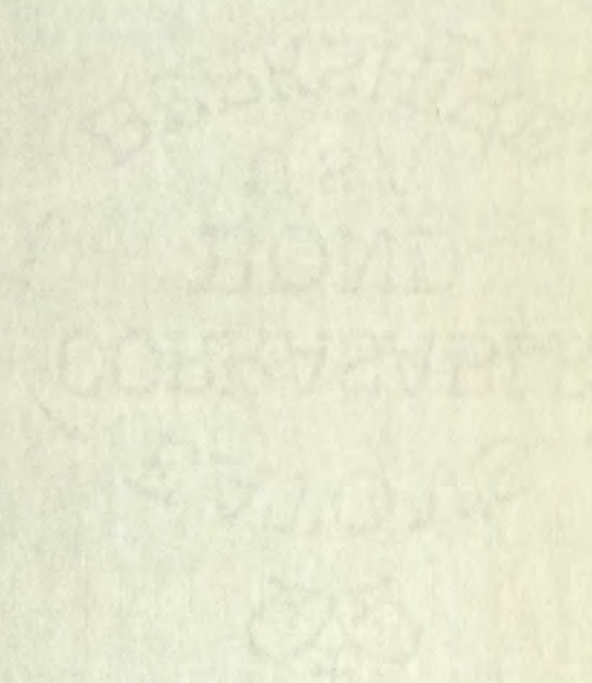
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WILLIAM CORLETT

1875-1945

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