NONLINEAR-MAGNETIC CONTROL DEVICES

Basic Principles, Characteristics, and Applications

By WILLIAM A. GEYGER

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PREFACE

The term "nonlinear magnetics" describes a wide field of electrotechnology in which the nonlinearity of the magnetic saturation characteristic of "soft," or easily magnetized, ferromagnetic materials and saturation phenomena are utilized to obtain some useful results. Typical examples are the stabilization of supply voltages or reference currents, frequency multiplication, magnetic modulation and/or amplification, static d-c to a-c power conversion, and the application of memory effects in counting reactors and in digital-computer systems. During the past decade the term nonlinear magnetics corresponding to similar words, such as electronics, cybernetics, and cryogenics, has gained wide acceptance for characterizing the broad field of activity of technical committees and the subject of papers to be presented in official scientific meetings and special technical conferences.

Utilization of the nonlinear properties of saturable-core elements in transformerlike structures for the design of "static" control devices does meet the universal requirements for simple and reliable components in electrical equipment. For this reason, nonlinear-magnetic control devices are found today in practically every branch of industry and in military installations. In recent years, they have been widely used in utility and communication systems, nuclear power plants, guided missiles, artificial earth satellites, and other types of spacecraft. Many applications of nonlinear-magnetic control devices are concerned with recent developments in the realm of instrumentation, automatic control, and analog-computer technique. Closely related to these developments are the numerous applications of switching-transistor magnetic-core multivibrators acting as efficient static d-c to a-c power converters, regulated d-c power supplies, voltage-to-frequency transducers for telemetering, or other kinds of auxiliary devices.

In view of this situation, a knowledge of the basic principles, characteristics, and applications of nonlinear-magnetic control devices has become a valuable asset to engineers, teachers, and patent lawyers. In regard to the extreme importance of these versatile devices and their various applications to modern electrical engineering practice, the time has certainly come when this subject should be presented to all students of physics and electrical engineering. There is, however, no complete analysis published of the very extensive literature dealing with nonlinear-magnetic control devices, though there are several discussions on certain portions of the field in some recent books covering the magnetic-amplifier art. Since most of the available knowledge concerning other types of such devices is to be found in widely scattered places in the bulk of scientific papers, domestic and foreign patents, and other technical publications, it was felt that it would be useful to provide a compact survey on this material. Such a compendium in the form of a reference book illustrates the current state of knowledge of the various nonlinear-magnetic control devices and will give the busy practicing engineer, patent attorney, research worker, and advanced student a general view of the whole subject.

This book, an attempt to fill the existing gap in the technical literature, is designed to be as simple as possible in treatment and should be useful for self-instruction. It develops logically the various kinds of nonlinear-magnetic control devices and represents a source of detailed information with extensive reference material including domestic and foreign patents. In view of the general aim of this guidebook, as much emphasis as is feasible is placed on experimentally observed phenomena and practical applications. Thus, extended mathematical considerations and cumbersome proofs are avoided, and descriptive and graphical methods are used to give a qualitative and quantitative interpretation of the essential facts. In most cases, an attempt is made to give, not a rigorous mathematical analysis of the described arrangements, but rather a physical picture of the operation by sketching the waveforms of voltages and currents existing within the saturable-core circuits. In regard to these aspects, nearly all of the mathematical treatment is of the most elementary nature, and great care has been taken to keep the nomenclature and symbolism logical, distinct, and clear.

In writing this book, the foremost thought in the author's mind has been to set out fundamental principles and the relationships between them. Hence, specific circuits are used only as concrete illustrations of the more general underlying principles. Regarding this point of view, a considerable amount of introductory material has been presented which does provide a smooth transition from basic concepts on magnetic circuits, electromagnetic induction, and waveforms to the fundamental principles of nonlinear-magnetic control devices. Because these devices are based upon the nonlinearity of the magnetic characteristic and saturation phenomena in magnetically soft core materials, such as high-permeability nickel-iron alloys, a brief review is presented on static and dynamic hysteresis loops of such materials, including the respective units and definitions. Emphasis is placed here on special core materials having an almost rectangular hysteresis loop, generally termed "square-loop materials," and on the various forms of idealized *B-H* characteristics, as used in analytical treatment of nonlinear-magnetic control devices.

The layout of the circuit diagrams has been conducted consistently so that comparison of similar circuit arrangements and recognition of identical features, similarities, or essential differences is facilitated. In these diagrams, the saturable-core element is symbolized by either ring-shaped or rectangular core structure with associated windings, which clearly illustrate the proper connection of the terminals of the winding units with the other parts of the circuit. In this way, confusion is eliminated because the respective direction of currents and magnetic-flux components can be easily recognized. Furthermore, the use of this graphical symbol discriminating between saturable-core elements and ordinary transformers with unsaturated cores has proved to be particularly valuable in the treatment of more complex arrangements, such as push-pull-type and three-phase-operated saturable-reactor devices, flux-gate magnetometers, frequency multipliers, and switching-transistor magnetic-core multivibrators.

Before describing contents of the fourteen chapters of this book, a few comments regarding its general plan may not be out of place. First, the book, as its title implies, deals primarily with those types of nonlinear-magnetic devices which are "controlled" in some way by certain electric or magnetic quantities to provide automatic regulation, magnetic modulation or amplification, frequency multiplication, static d-c to a-c power conversion, or various methods for d-c instrumentation. However, certain remotely related devices such as magnetic logic circuits, analog computers and digital programmed systems utilizing nonlinear-core characteristics, and magnetic-tape equipment are entirely omitted, as they are adequately treated in recent excellent books on these subjects.

Second, attention is confined to nonlinear-magnetic control devices used in the frequency range of about 50 to 100,000 cps. Although those used in radio-frequency systems fall outside the declared scope of this book, numerous references to this related field have been included and briefly discussed.

Third, the book does not consider those design problems which are concerned with compromises on simultaneously satisfying the requirements of electromagnetic principles and the stern laws governing the economic production of a salable article. However, in view of this quite important aspect, the specific technical properties and advantages of similar devices are evaluated and compared in some cases. At the same time an attempt has been made at a critical appraisal of those devices which have been found best for the solution of specific problems. Here again, the idea is to teach concepts through selected examples of preferred circuit arrangements.

As the book is intended primarily for practical use, every endeavor has been made to make clear the experimental side of the subject and to incorporate detailed information on core and winding data of various prototype designs. This has been done because the author firmly believes that the best way to learn about such devices is to use them. Indeed, for an elementary course in the subject matter nothing could be better than a properly arranged series of simple experiments on breadboard models. By generously presenting these core and winding data an opportunity is given to the reader to become familiar with such circuit arrangements and to obtain a suitable point for starting elementary experiments which may lead later to experimental investigations on more complex systems.

In view of his extensive studies of domestic and foreign technical literature concerning the various kinds of nonlinear-magnetic control devices, including the numerous volumes of American, British, French, German, Swedish, and Swiss patents on this subject, the author is fully aware of the fact that only a fraction of the relevant reference material could be used in the space available in this book. Therefore, in the following treatise, each group of these devices will be described by means of typical examples, suitably selected, with special reference to the original literature. However, because a considerable part of foreign technical literature which is provided at the end of each chapter may not be readily accessible to the general reader, respective references to summarizing papers of the extensive literature published in the United States have been added in many cases. This procedure in presenting the very large amount of reference material is considered to be particularly useful to the research worker in many branches of electrotechnical and physical investigations.

Reference to the literature shows that research and development work on nonlinear-magnetic control devices has rapidly increased during the past fifteen years, both in this country and abroad. It also makes it evident that the term "magnetic amplifier" is quite attractive and is generally applied today to many saturable-core devices not involving amplification or modulation, and even to some remotely related arrangements having saturable cores. This may be a result of the growing popularity of the magnetic amplifier since its rebirth during and after the Second World War and of the numerous successful applications of various types of magnetic amplifier in modern electrotechnology.

Experience has also shown that it is nearly as hard for engineers in the magnetic-amplifier art to agree on definitions of the terms saturable reactor, transductor, and magnetic amplifier as it is for them to accept definitions for respective terms, such as feedback, self-saturation, self-excitation, auto-self-excitation, and self-balancing techniques utilizing infinite internal gain. The author, when outlining and writing this book, had to come to a clear decision concerning acceptable answers to such questions of terminology. Therefore, the classification of devices and the definitions of terms are presented here in a way which, it is hoped, will be of value not only to research workers, professional engineers, and teachers, but also to the newcomer in this field.

In its Introduction the book describes briefly the historical development of nonlinear-magnetic control devices with special reference to the rapid progress in the past decade. Referring to the scope of this book and to the afore-mentioned limitations concerning remotely related devices, it is pointed out that the present treatment is based upon a classification with regard to the various fields of practical applications.

Chapter 1 deals with elementary concepts concerning static and dynamic hysteresis loops of magnetically soft core materials. It describes methods for measurement of hysteresis loops and the idealized *B-H* characteristics, as used in analytical treatment of nonlinear-magnetic control devices. Chapter 2 describes combinations of a-c-saturated nonlinear inductors (without direct-current magnetization) and linear-impedance elements. Chapter 3 gives a description of the application of saturating-core circuits to representative practical problems, with special reference to magnetic voltage stabilizers and reference circuits. This presentation includes contact converters with commutating reactors, lead networks utilizing memory effect of saturating reactors with square-loop core material, counting reactors, and timers.

Chapter 4 describes the fundamental principles and technical properties of the ordinary saturable reactor (without feedback). It presents analytical considerations and the theoretical waveforms corresponding to operation of such devices with either "free" or "suppressed" even-harmonic currents. Chapter 5 gives a survey on the application of ordinary saturable reactors in d-c instrumentation. It presents a comparison between actual control characteristic and the ideal ampere-turn characteristic, deals with miniaturized d-c instrument transformers to be used in earth-satellite equipment, and describes modern forms of large d-c instrument transformers, as used for the measurement of large bus-bar currents up to 150,000 amp and high d-c voltages up to about 220,000 volts, with reference to the original literature. This chapter also discusses briefly the properties of ordinary saturable reactors with three-phase power supply. These devices have come to be regarded as standard for high-power saturable-reactor applications reaching today into the 1,000-kw area.

Chapter 6 deals briefly with two-core saturable-reactor devices utilizing feedback techniques. These systems are widely used as magnetic amplifiers with external or internal positive feedback. The treatment emphasizes the extreme importance of the fundamental relationship between power gain, linearity error, and response time. This relationship is such that if one property is accentuated, it is always at the expense of the other properties. It is stressed that the occasionally dramatized achievement of half-cycle-response operating conditions of the magnetic amplifier is significant only in special applications, which require minimum response time of the amplifier. Actually, the speed of response of the amplifier should be just high enough to meet the dynamic requirements of the specific control problem. In view of these facts, the treatment in this chapter also emphasizes "self-balancing" magnetic amplifiers operating with voltage-balance or current-balance conditions of the control circuit and with infinite internal gain. This chapter also refers to the extensive literature covering the feedback-type saturable-reactor systems with three-phase power supply. Chapter 7 describes in a similar way the push-pull-type saturable-reactor devices having four cores.

Chapters 8 and 9 give a detailed description of magnetic frequency multipliers with single-phase or three-phase power supply, respectively. Chapter 10 describes the magnetic frequency multipliers of the shock-excitation type. This presentation includes a brief treatment of saturating-core frequency dividers.

Chapter 11 presents a detailed survey on switching-transistor magnetic-coupled multivibrators. Such devices are extensively used as a square-wave power supply for magnetic amplifiers, induction motors, gyros, and torque relays. They are finding an increasing application in d-c power-supply devices and may also be employed as voltage-to-frequency transducers for telemetering and as square-wave generators in magnetic-amplifier transient analyzers and magnetic-switch *B-H*-loop tracers.

Chapter 12 summarizes the state of the art concerning magnetic modulators from the electrical engineering standpoint. It describes briefly those fundamental-frequency and second-harmonic saturable-reactor devices which have proved to be useful as static d-c to a-c signal converters operating, in a modulated-carrier system, in conjunction with vacuum-tube or transistor-type a-c amplifiers. This chapter includes recent developments such as ferrite-core cross-field modulators and single-toroidal-core modulators with Supermalloy ultrathin-tape bobbin cores.

Chapter 13 deals with flux-gate magnetometers, which are widely used today for measuring external magnetic fields, for example, geophysical exploration by detecting magnetic anomalies of the earth's field. This presentation includes the latest developments, particularly the second-harmonic "ring-core magnetometer" using an ordinary toroidal core as the field-sensitive flux-gate element, and gradiometer systems. It also describes the self-saturating type of ring-core flux-gate magnetometer employing either a half-wave circuit of a full-wave system.

Chapter 14 presents a survey concerning typical applications of flux-gate magnetometers and gradiometers, with special reference to the extensive literature. This subject, of course, is considered to be particularly interesting in view of modern applications of miniaturized, lightweight magnetometer systems in earth-satellite equipment with solar-battery power supply.

In writing these chapters, every effort was made to give a full account of modern tendencies, particularly those concerning advantageous combinations of magnetic cores, transistors, and silicon-controlled rectifiers. The author placed emphasis on discussion of those arrangements not mentioned or only very briefly discussed in other books. The reader will also find a certain amount of new material which is presented here for the first time. In order to bring the reference material up to date, recently published technical papers and patents have been added to the lists of references at the last minute when revising the proofs for press.

Of course, in writing the book, certain limitations were imposed at the outset, and many interesting principles and devices have been mentioned only briefly because of space limitations. Indeed, some of the many topics covered in the individual sections could well occupy entire books themselves. If some parts of the subject are not as completely treated as the reader and, indeed, the author would have wished, consolation may be found in the fact that full references to readily accessible literature are given so that anyone who is interested may easily find further information.

The author believes that this book will be of value to the many thousands of practicing engineers, research workers, patent counselors, teachers, students, and newcomers who are interested in this fascinating field of electrotechnology. He wishes to express his appreciation to his many friends and associates, both in the U.S. Naval Ordnance Laboratory and elsewhere, for their helpful cooperation in encouraging him to write this book.

William A. Geyger

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Introduction

HISTORICAL DEVELOPMENT OF NONLINEAR-MAGNETIC CONTROL DEVICES

The fascinating possibility of utilizing the nonlinear properties of magnetic core materials for the design of "static" control devices has attracted interest since the beginning of the century. One of the earliest disclosures (C. F. Burgess and B. Frankenfield, 1901)[1] describes the use of direct-current premagnetized saturable reactors as an advantageous method of regulating and controlling alternating currents whereby a multiplicity of contacts and moving parts of any kind are eliminated. Another early application (H. J. Ryan, 1901)[2] is a null method employing a d-c premagnetized transformer for measuring large direct currents in the range of 100 to 1,000 amp with an accuracy of about ± 0.5 per cent, without the use of shunt resistors. In the same year (R. A. Fessenden, 1901),[3] the basic idea of using a saturable reactor in a "wireless signaling" system as a magnetic modulator was presented. Also at that time, a static frequency multiplier (J. Epstein, 1902)[4] based upon superposition of a-c and d-c magnetization in transformerlike structures was introduced.

The term "magnetic amplifier" appears first in E. F. W. Alexanderson's patents (1912 to 1918)[5] on applying a saturable-reactor system as voice-frequency modulator for radiotelephony and transoceanic radio communication. Independently, during this period, special forms of magnetic modulators for radiotelephony were developed by German engineers.[6] Other work in Germany (1910 to 1925) was concerned with the application of magnetic frequency multipliers in conjunction with high-frequency alternators for reliable operation of radio transmitters.[7,8] This method made it possible to overcome the critical threshold in alternator frequency.

During the era following many successful applications of magnetic amplifiers, modulators, and frequency multipliers, both in this country and abroad, these arrangements became of minor importance in the field of radio engineering because of rapid progress in vacuum-tube techniques. However, the extensive collections of German and United States patents covering this subject[9,10] indicate that development of these static-control devices has been conducted continuously up to the present.

The revolutionary results obtained in the thirties by application of nickel-iron-alloy core materials to current-transformer construction[11] did lead to an equally important and successful development work in Germany concerning various deflection methods for the measurement of large direct currents, without the use of shunt resistors, by means of saturable-reactor devices, similar to those introduced in 1913 by E. Besag.[12] However, although significant advantages resulting from application of high-permeability nickel-iron alloys in saturable-reactor design had been recognized early (G. Keinath),[13] decisively important new developments on high-performance "d-c instrument transformers" (*Gleichstrom-Messwandler*) were not made until several years later (W. Krämer, 1937 to 1939).[14–16] These developments are based upon the recognition that properly rated saturable reactors with nickel-iron core material have inherent current-transformer characteristics (*echte Stromwandler-Eigenschaften*).

Krämer's publications greatly stimulated development in Germany and Sweden. In the Scandinavian countries the rather long expressions "d-c premagnetized choke coil" and "saturable reactor" were replaced by the term "transductor," a compound of the words transformer and inductor.[17–20] Many techniques involving special combinations of saturable-reactor elements and metallic rectifiers for supplying controllable d-c power from single-, three-, and six-phase networks in place of the conventional mercury-arc-rectifier systems were developed at that time by Allmänna Svenska Elektriska Aktiebolaget (ASEA) personnel. These techniques including the "Nordfeldt connection"[21] are particularly suitable for installations with large power outputs.

In the 1930s, large tape-wound ring cores with toroidal windings were applied as "commutating reactors" to aid commutation among the contacts of mechanical rectifiers. The pioneer work of F. Koppelmann[22] made the successful design and operation of large-power contact converters possible by the application of special core materials having an almost rectangular dynamic hysteresis loop. In Germany, such contact converters with synchronously operated contact mechanism are employed instead of mercury-arc rectifiers for converting very large alternating currents (up to 10,000 amp) into unidirectional currents with the unusually high efficiency of about 98 per cent. Actually, at that time, this work was one of the main reasons why extensive German research and development had been devoted to special magnetic materials, such as Permenorm 5000-Z. Closely related to this activity was the development of very refined alternating-current measurement techniques[23] which made it possible to investigate such materials properly and to evaluate their magnetic properties with regard to the successful construction of large-power contact converters.

In 1934–1935, H. Aschenbrenner and G. Goubeau[24] applied a second-harmonic type of flux-gate magnetometer for recording the changes in intensity of the earth's magnetic field. This extremely sensitive magnetometer is particularly suitable for geophysical measurements, testing of nonmagnetic materials (*e.g.*, detection of ferromagnetic particles in aluminum rods or copper wire), and for military applications ("airborne magnetometer"). Extensive work on the second-harmonic type of flux-gate magnetometer[25] was carried out shortly before and during the Second World War, both in this country and abroad. During the same period, extensive research and development was conducted in a similar and equally important field concerning the conversion of low-level, polarity-reversible, d-c signals into phase-reversible a-c voltages, with a high degree of zero stability, through the use of a second-harmonic type of magnetic modulator acting as a static d-c to a-c signal converter.

The enormous advance which had been made in Germany, several years before and during the Second World War, in the development of various magnetic-amplifier systems was largely the result of the availability of high-permeability nickel-iron core materials and the rapid progress in manufacturing of efficient and reliable metallic, *e.g.*, selenium-type "dry-disk," rectifiers. This extensive development work was based upon the fact that there are certain military applications for amplifiers of electric signals which require that these amplifiers possess unusual durability, simplicity, and reliability. Pioneer work on the single-phase push-pull type of saturable-reactor circuit as a high-speed magnetic amplifier for various applications (*e.g.*, in autopilots, blind-approach systems, remote-control positional servomechanisms, and computer circuits) and as a very sensitive fundamental-frequency type of flux-gate magnetometer was carried out, at that time, by G. Barth[26] and G. Rudolph[27] and their staff. Both naval and air force equipment was produced by Siemens Apparate & Maschinen (SAM) personnel.

In the author's experience, nonlinear-magnetic control devices made their first appearance in special instrumentation work concerning the operation of vibrating-reed and ink-recording types of frequency meter[28] and the use of magnetic frequency multipliers for supplying alternating-current bridge and potentiometer circuits.[29] Further work (1940–1943)[30] concerned replacing the mechanical d-c to a-c signal converter ("chopper") and the vacuum-tube a-c amplifier, as used in high-speed recording potentiometers, by a high-performance, d-c controlled magnetic servo amplifier operated from a 50-cps power supply. This magnetic amplifier of the balance detector type (*magnetischer Nullstrom-Verstärker*)[31] was designed to have duodirectional input-output characteristic, high sensitivity (large power gain), and an extremely small zero-drift rate. The output power of this push-pull-type amplifier was sufficient for the control of a small reversible motor, which was either a separately excited, induction-type, two-phase motor or a d-c motor of the d'Arsonval-meter type.

Also at that time, the author[32] devised a d-c amplifier of the modulated-carrier type which uses a push-pull magnetic amplifier as a static d-c to a-c signal converter with high zero stability. Combination of this arrangement with standard d-c ink recorder made it possible to produce a permanent record of very small direct voltages or currents, created, for instance, by thermocouples, strain-gage bridge networks, photoelectric cells, or radiation pyrometers.

Early in 1944, C. S. Hudson[33] initiated work on magnetic amplifiers at the Royal Aircraft Establishment, which was concerned mainly with amplifiers designed to operate from a 400-cps power supply. This work and detailed examination of German designs[34] may have reawakened interest in magnetic amplifiers in England. Several years later, theoretical and experimental studies of the magnetic amplifier utilizing positive-feedback techniques were published by British authors.[35–37] In England, the term transductor, introduced by Scandinavian investigators, has gained wide acceptance for describing high-performance saturable reactors or magnetic amplifiers with nickel-iron-alloy or other types of rectangular-hysteresis-loop core materials. Also, in recent German publications[38] the term *Transduktor* has been introduced. This is in contrast to publications on magnetic amplifiers in the United States, where the term transductor is seldom used in view of possible and actually quite frequently observed confusion with the word "transducer," as applied for describing any device which converts a variable *nonelectric* quantity to be measured into a corresponding *electric* value.

One reason for the increased interest in magnetic amplifiers in this country, immediately after the Second World War, was the successful German development work for various military applications, especially for naval fire-control systems, as used on the German heavy cruiser "Prinz Eugen."[39] The comprehensive "Bibliography of Magnetic Amplifier Devices and the Saturable Reactor Art," presented by J. G. Miles,[40] makes it evident that the number of scientific papers, technical reports, and United States patents published each year during the period from 1900 to mid-1951 steadily increased. Two committee reports[41] of the American Institute of Electrical Engineers covering domestic and foreign literature for the years 1951 through 1957 reveal that the number of respective publications continuously increased every year, exceeding two hundred in 1956 and 1957. For the ensuing period until the present time, the number of yearly publications on nonlinear-magnetic control devices has been about two hundred, in accordance with the author's recent survey including recently published German patent applications.

A very significant indication of the increased interest and activity in the field of nonlinear-magnetic control devices is that standardizing groups of the American Institute of Electrical Engineers are working on definitions and methods of expressing the performance characteristics of magnetic cores and magnetic amplifiers.[42] This extensive work includes considerations of various educational aspects.[43,44] It has been performed, since 1948, by the Magnetic Amplifiers Committee of the AIEE. Recently, the name of this committee was changed to Nonlinear Magnetics Committee in view of the considerably broadened field of its activity, which is concerned also with many related nonlinear-magnetic devices, such as ferroresonant circuits, magnetic frequency multipliers, switching-transistor magnetic-core multivibrators, flux-gate magnetometers, and combinations of magnetic-core arrangements with various types of semiconductor devices.

Besides the numerous papers which have been presented on these subjects at each of the AIEE General Meetings for the past fifteen years, many papers have been given, each year since 1956, at the Special Technical Conferences on Magnetic Amplifiers or Special Technical Conferences on Nonlinear Magnetics,[45] which are sponsored jointly by the American Institute of Electrical Engineers, the Institute of Radio Engineers (now merged into the Institute of Electrical & Electronics Engineers, briefly termed IEEE), and the Instrument Society of America (ISA). These special technical conferences provide an opportunity for engineers and scientists associated with universities, government research laboratories, and both small and large manufacturing companies to present and discuss new developments in the field of nonlinear-magnetic control devices. In accordance with modern tendencies concerning applications of saturating-core arrangements in conjunction with various semiconductor devices, the recent special technical conferences on nonlinear magnetics, particularly the IEEE International Conference on Nonlinear Magnetics (Intermag Conference, Washington, D.C., April 17–19, 1963), included many papers on special combinations of magnetic cores, transistors, tunnel diodes, and silicon-controlled rectifiers.[46]

The enormous development of nonlinear-magnetic control devices within the past decade is largely the result of many improvements concerning engineering of toroidal, either tape-wound or laminated (washer-type), nickel-iron-alloy cores and their manufacturing processes. The consistent uniformity of commercially available toroidal cores, in standardized sizes, makes it possible to provide such cores in matched sets having almost identical magnetic characteristics. The modern forms of either plastic or aluminum protective boxes permit application of toroidal cores with unusual environmental conditions, such as very high temperatures or extremes of mechanical shock or vibration.

The introduction of ultrathin, ⅛-mil to ½-mil, nickel-iron-alloy tape[47] wound on ceramic or stainless-steel bobbins ("bobbin cores") made it possible, for example, to extend the power-supply-frequency range of magnetic amplifiers to about 50,000 cps. As a result, recent development work concerning audio-frequency applications of magnetic amplifiers was successful,[48] and quite remarkable sound performance has been obtained when using "self-balancing" high-speed magnetic amplifiers[49] with 40,000 cps in conjunction with a crystal-type radio receiver or standard turntable equipment.[50]

In view of the various applications of nonlinear-magnetic control devices in earth-satellite equipment with solar-battery supply, special low-power-operated systems have been developed recently. A new type of second-harmonic flux-gate magnetometer utilizes an ordinary toroidal core without air gap as the field-sensitive element.[51–53] Because this "ring-core flux-gate magnetometer" has very low magnetizing-current requirements, the power drain on the solar battery is about 50 mw, or less. This miniaturized design has proved to be useful in many applications where small size, light weight, and very low power drain are of prime importance.

Another recent development provided a low-power-operated d-c instrument transformer.[54] In this push-pull design, which is 60-cycle operated from a small switching-transistor magnetic-core multivibrator, actual power drain on the 6-volt battery is less than 5 mw. Such battery-operated arrangements are also useful for industrial applications in the realm of control engineering because the low-power battery operation makes reliable function of these devices independent of the 60-cycle line voltage and possible interruptions of supply.

In addition to such developments, numerous theoretical and experimental studies have been made concerning the construction of saturable-reactor elements, which is closely linked with the specific properties of the nickel-iron core materials. Other extensive studies are concerned with modern procedures for testing, grading, and matching of magnetic cores. Particularly important is, of course, the high-precision measurement of dynamic hysteresis loops. The recently introduced "Ferrotracer"[55] operating in conjunction with a standard x-y recorder produces in about 30 sec an immediate, direct, and permanent record of dynamic B-H loops, not requiring subsequent photographic processing.

The advent of silicon junction diodes having very low forward resistance and extremely high reverse resistance, even with wide temperature variations, had a tremendous influence on development, construction, and special applications of nonlinear-magnetic control devices. Today, small-size germanium diodes and silicon diodes have replaced here the previously employed selenium-type or copper-oxide-type "dry-disk rectifiers." Actually, only by matching the low-coercive-force core material (requiring a relatively small magnetizing current) to feedback rectifiers of correspondingly small reverse current was it made possible to materialize the full advantages of such core materials with regard to self-saturating magnetic amplifiers utilizing large amounts of positive feedback.

The combination of high-permeability toroidal cores with various types