HANDBOOK OF TRANSFORMER APPLICATIONS

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Preface

Magnetic components are the product of a mature industry. Being away from the cutting edge of technology, they sometimes do not receive the attention which their economic significance requires. Misunderstanding and lack of information cause many magnetic applications to cost more than they should. This handbook is an attempt to help relieve this problem by providing updated information which heretofore has been widely scattered.

User and supplier frequently use different language and have opposing viewpoints. The resulting faulty communications are at the root of many of the difficulties encountered with magnetic devices. An objective of this book is to facilitate this communications process. Ultimately, the aim of all parties is to secure—in the shortest possible time and at the lowest possible cost—components which function correctly. Mutual understanding and a broad common technical base are important contributors to this aim. Because of the great importance of mechanical requirements to magnetic components, sections of this work are devoted to current mechanical and manufacturing practice as well as to electrical theory. Space is also devoted to specification preparation, testing, and quality control—factors which relate directly to both user and supplier.

The author is indebted to many people for assistance and encouragement in writing this book. His family, both immediate and extended, have provided indispensable support. His associates [illegible] Electronics

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William M. Flanagan

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CHAPTER 1

Magnetic and Electrical Fundamentals

1.1 INTRODUCTION

Transformers are passive devices for transforming voltage and current. They are among the most efficient machines, 95 percent efficiency being common and 99 percent being achievable. There is practically no upper limit to their power-handling capability, and the lower limit is set only by the allowable no-load loss. Transformers and inductors perform fundamental circuit functions. They are a necessary component in electrical systems as diverse as distribution terminals for multimegawatt power-generating stations to hand-held radio transceivers operating on a fraction of a watt. This book is intended to ease some of the difficulties users and designers face from the limitations of these components, the resolution of which is still painfully evolving.

Transformers are the largest, heaviest, and often costliest of circuit components. The geometry of the magnetic circuit is three-dimensional. This property places a fundamental restraint on reducing transformer size. The properties of available materials limit weight reduction. The high cost of transformers is due to the impracticability of standardization, the materials needed, and the processes inherent in their manufacture. The problems associated with the use of magnetic devices can be minimized by the employment of astute application practices.

Transformers are indispensable for voltage transformation in power applications. Their ability to isolate circuits and to alter ground conventions can often be matched in no other convenient manner. They are needed in frequency selective circuits whose operation depends on the response of inductances. They are rugged, being capable of withstanding severe environmental conditions.

Transformers are essentially single-application devices. Designed for specific requirements, they do not offer optimum performance over a wide range of operation. They are not outstanding performers in applications requiring high-fidelity reproduction of audio or video signals. Wideband and high-impedance circuits often experience serious degradation when transformers are used. Transformers do not perform well in circuits which apply dc magnetization to the core. They are a problem in equipment in which size and weight must be kept to a minimum.

Transformers can sometimes be eliminated by circuit artifices. A bridge rectifier directly across the power line can replace a power transformer and rectifier if the voltage level and ground isolation can be accommodated. This is often done to obtain dc voltage for inverter circuits. Needed voltage transformation is then done at high frequency with a much smaller transformer. The direct coupling of semiconductor devices to loads eliminates audio transformers. Operation of driving circuits at voltages which will provide the desired output voltage by direct coupling may eliminate the need for voltage transformation at the output.

Closely related in both theory and construction to transformers are other magnetic devices which include inductors, saturable reactors, and magnetic amplifiers. Much of the discussion on transformers is applicable to them. The unique features of these devices are discussed separately.

1.2 FUNDAMENTALS OF MAGNETIC CIRCUITS

The literature on magnetic devices uses a vocabulary which may be unfamiliar to some readers. It is not difficult to learn these terms and to master the fundamentals of magnetic circuits. This section provides an introduction to the subject.

The study of magnetics begins with Coulomb's law for magnetic poles:

$$F = \frac{m_1 m_2}{\mu r^2} \tag{1.1}$$

where F = repulsive force between two magnetic poles of like polarity m_1 and m_2

r = distance between the two poles

μ = constant of proportionality called *permeability*

Units are chosen so that μ is equal to 1 in air. The poles m_1 and m_2 are mathematical fictions useful in defining relationships. If both sides of Eq. (1.1) are divided by m_2 and m_2 is assigned unit magnitude, then a new quantity, magnetizing force, symbol H, is defined:

$$H = \frac{F}{m_2} = \frac{m_1}{\mu r^2} \tag{1.2}$$

If m_1 and m_2 are both of unit magnitude, the magnetizing force will be of unit magnitude. The unit for H is called the *oersted* (abbreviated Oe).

Work is done in moving a unit test pole m_2 in the magnetic field associated with a magnetizing force. The integration of H with respect to r as r changes during the motion of m_2 gives the work done. The work done is called magnetomotive force (mmf):

$$\text{mmf} = \int_{r_2}^{r_1} H\,dr = \frac{m_1}{\mu r_1} - \frac{m_1}{\mu r_2} \tag{1.3}$$

The commonly used unit for mmf is the gilbert. An oersted is one gilbert per centimeter. Another convenient term for mmf is *ampere-turn,* and when it is used the magnetizing force is in ampere-turns per inch.

Permeability μ is a function of the medium. Since magnetic circuits frequently involve more than one medium, another term which is independent of the medium is used. This term, called *flux density,* symbol B, is obtained by multiplying both sides of Eq. (1.2) by μ:

$$B = \mu H = \frac{m_1}{r^2} \tag{1.4}$$

The unit for B is gauss. In air, where the permeability μ is 1, one oersted is equivalent to one gauss.

The flux density around a point pole m_1 will be uniform at a constant distance from the pole. The total flux emanating from the pole will be the flux density at a distance r from the pole multiplied by the area of a sphere of radius r with the pole m_1 at the center:

$$\phi = BA = \frac{4\pi r^2 m_1}{r^2} = 4\pi m_1 \tag{1.5}$$

The total flux is independent of the medium and will be continuous across spherical boundaries between media of different permeabilities surrounding the pole m_t. The unit of flux is the maxwell. One gauss is one maxwell per square centimeter. One kilogauss is one thousand gauss per square centimeter. One thousand maxwells per square inch, commonly referred to as *kiloline per square inch,* and kilogauss are both commonly used units for flux density.

Magnetic flux is analogous to current in an electric circuit, and magnetomotive force is analogous to voltage. This suggests Ohm's law for magnetic circuits:

$$\text{mmf} = \phi \mathcal{R} \tag{1.6}$$

In magnetic circuits the proportionality constant in Ohm's law is called *reluctance,* symbol $\mathcal{R}$. Reluctance is directly proportional to the length of the magnetic path and inversely proportional to the area through which the flux flows, the proportionality constant being permeability:

$$\mathcal{R} = \frac{l}{\mu A} \tag{1.7}$$

Reluctance does not have a unit assigned. The term gilberts per maxwell is sometimes used. In that system of units, the dimensions are in centimeters and μ is 1 for air.

Permeability is an important property of magnetic circuits. Ferromagnetic materials have permeabilities of 1000 or more. Air, insulating materials, and most electric conductors except ferromagnetic materials have permeabilities of approximately 1.

The permeability of ferromagnetic materials is not constant. It varies with frequency, waveshape of applied signals, temperature, and flux density. It is not even a single-valued function. The double-valued nature of permeability gives rise to the well-known hysteresis curve, which is only approximate, varying from batch to batch of the same material. The elusive nature of permeability is one reason that the study of magnetic devices appears somewhat esoteric. The analysis of magnetic circuits generally uses constant and single-valued approximations for permeability over a limited range. Selecting these approximations and their boundaries is a major task of magnetic design. See Secs. 1.6 and 6.4 for a further discussion of the permeability of magnetic materials.

1.3 CURRENT, FLUX, AND INDUCTANCE IN MAGNETIC CIRCUITS

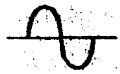
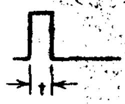
A current flowing in a straight conductor generates a magnetic field around the conductor, the intensity of which is proportional to the magnitude of the current. It is convenient to think of the magnetic field as consisting of flux lines around the conductor. These lines are continuous and tend to repel each other. They form concentric circles with the conductor at the center of the circles. The plane of the circles is perpendicular to the conductor. The direction of the flux circles, either clockwise or counterclockwise, will reverse if the current reverses. The number of flux lines is proportional to the total flux around the conductor. The flux lines will be close together near the conductor and become farther apart as the distance from the conductor increases. Where the lines are close together, the flux density B is higher than where the lines are farther apart. The separation between adjacent flux lines increases indefinitely as the distance from the conductor increases, each circle of flux meanwhile remaining continuous around the conductor.

Imagine a plane passing through the conductor and its magnetic field. The flux lines will pass through the plane in one direction on one side of the conductor and in the opposite direction on the other side of the conductor. If this conductor is formed into a closed loop, all the flux lines which were on one side of the plane will now tend to be concentrated in the area enclosed by the conductor. If additional conductor turns are made around the area, forming a coil, additional flux lines are added within the enclosed area. If all the flux lines are contained in the area, the number of flux lines will be proportional to the product of the current and the number of turns.

The magnetic field associated with the turns of wire or coil is an energy reservoir. The current that will flow through the conductor when a voltage is suddenly applied across the coil must supply the energy contained in the magnetic field. The current will start at zero and rise at a rate proportional to the applied voltage. When the applied voltage is removed, the energy in the magnetic field is returned to the electric circuit in the form of a voltage appearing across the coil which is proportional to the rate of change of the current. Because the flux is proportional to the current, energy transfer between the circuit and the magnetic field will occur only when the current is changing. These considerations lead to the defining relationship for inductance:

$$e = L\frac{di}{dt} \tag{1.8}$$

TABLE 1.1 Maximum Flux Density Formulas for Commonly Occurring Functions

Function	*Waveform*	*Formula*
1. Sine wave voltage (steady-state)		$B_{max} = \dfrac{E_{rms} \times 10^8}{4.44NAf}$
2. Symmetrical square wave voltage		$B_{max} = \dfrac{E_{pk} \times 10^8}{4NAf}$
3. Interrupted symmetrical square wave voltage		$B_{max} = \dfrac{E_{pk} \times t \times 10^8}{2NA}$
4. Half sine wave voltage pulse		$B_{max} = \dfrac{E_{pk} \times 2 \times t \times 10^8}{\pi NA}$
5. Unidirectional rectangular voltage pulse		$B_{max} = \dfrac{E_{pk} \times t \times 10^8}{NA}$
6. Full-wave-rectified single-phase sine wave voltage (ac component only)		$B_{max} = \dfrac{E_{dc} \times 10^8}{19.0NAf}$
7. Half-wave-rectified three-phase sine wave voltage (ac component only)		$B_{max} = \dfrac{E_{dc} \times 10^8}{75.9NAf}$
8. Full-wave-rectified three-phase sine wave voltage (ac component only)		$B_{max} = \dfrac{E_{dc} \times 10^8}{664NAf}$
9. Current	Any	$B_{max} = \dfrac{LI_{max} \times 10^8}{NA}$

Note: In these formulas N is the number of turns in the winding across which the voltage is developed. A is the cross-sectional area of the core around which the winding is placed. If the area is expressed in square centimeters, the flux density will be in gauss. If the area is expressed in square inches, the flux density will be in maxwells per square inch. Time t is in seconds. Frequency f is in hertz. Voltage E is in volts. Current I is in amperes. Inductance L is in henrys.