Methods of Magnetizing Permanent Magnets
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1. Introduction

Many people find magnets to be strange, mysterious things, and I think that physicists are puzzled a good deal more by them then they like to admit. Magnets have been with us a long time, in fact from our earliest history, long before formal science was started, or the mathematics we use to describe it. We all know what magnets do. Magnets have locations on them, called poles. Poles come in two types, which we call North-seeking poles, or just North poles, and South poles. They always occur in pairs of equal strength, although they may have more than just two poles, of course. Opposite pole types attract, while poles of the same type repel each other. Poles of either type attract iron, steel, and a few other metals such as nickel. These things have been known for thousands of years. Much more recently, that is in the last two hundred years, we have found out that electricity and magnetism are related, and most of the time today we will be talking about ways to use electricity to make certain special materials, called permanent magnet materials, to be magnetic. When magnets are first produced, they are usually not magnetic at all, or possibly they are only very weakly magnetic. For the magnet to have the properties we need, it must be magnetized. This can be done at the factory which first made the material, but for a number of reasons it usually is preferable to ship the parts in an unmagnetized state. The magnets are then either built into useful things like speakers, electric motors, generators, instruments, and such, and then magnetized in place, or else if necessary they are magnetized just before assembly. Some reasons why it is often preferred to magnetize parts at the assembly location are:

(1) It may be difficult or impossible, or dangerous for the workers, to assemble the intended product using a magnetized magnet, because of its attraction to steel parts or attraction/repulsion with other magnets.

(2) Permanent magnets in shipment may affect, damage, or even destroy other items in nearby packages, such as bank records, credit cards, watches, and so on.

(3) Large permanent magnets may pinch or crush body parts of persons working with the packages, or nearby.

(4) Permanent magnets may affect navigation instruments, especially in aircraft. Laws therefore govern the shipping of magnets.

(5) Magnetized magnets may pick up magnetically-permeable dirt, which is present almost everywhere. This dirt is often in the form of very tiny, long, pointed needles, which turn vertically to the surface due to action of he magnetic field. They are very difficult to see, and enter the hands of those moving the packages as splinters, which are painful, and difficult to locate and remove. The dirt seems to be derived from magnetite, from rusted iron, and also from iron and steel (perhaps from wear and spall). Magnetic dirt, once on the magnet, is very difficult to clean, as it will just move around a cleaning cloth, or fly back to the attracting surface if separated. The best way to remove it, to my knowledge, is to wrap masking tape around the hand with the sticky side out, and then gently! roll it onto the contaminated surface, being careful to avoid driving sharp particles through the tape and into your hand.

(6) Manufacturers often need control of the magnetizing process because of factors other than full magnetization, such as for example the effects of magnetic pattern on “cogging”, the tendency of a rotor to “jump” from one rotary position to the next, rather than to turn smoothly, due to magnetic effects. In some cases, this effect is desirable, as for example for magnetic clutches, but often it is harmful, causing inefficiency, noise, and vibration.

In addition to complete magnetization, there are some other magnetizing operations which are often needed. Measurements have to be made to insure that the magnets, as magnetized, meet the requirements of intended use. Sometimes errors are made in magnetization, handling, or assembly, or for other reasons parts must be demagnetized. Magnets are somewhat variable in strength, from one part to another, and often more from one batch of magnetic material to another. If this variation is too large for the needed purpose, then the magnets may be partially demagnetized by a small amount, to bring them to closer magnetic tolerances, in a process called "“conditioning"” In certain magnetic assemblies, conditioning of magnet strength may be done based on the performance of the entire device, rather than that of the magnet alone, thus removing an entire range of variables. This is done, for example, with some magnetic relays.

2. History

The earliest magnets were lodestone Ferric Ferrite, Fe_3O_4), a sort of natural magnet, related to today’s ceramic magnets. This material was a useful ore for iron, and was mined for that purpose in ancient times. The lodestone (which means “travel-stone”) was apparently magnetized from the Earth’s magnetic field, as it was deposited. By 1200 AD, compass needles were being made of steel, which were magnetized by being rubbed or “touched” with lodestones. In 1600 Gilbert recorded three ways to magnetize a steel needle: by touch with a lodestone, by cold drawing in a North-South direction, and by exposure for a very long time to the Earth’s field while in a North-South orientation. He also mentions that a magnet when brought to red heat is no longer magnetic, but that it would become magnetic if allowed to cool while pointing North-South.

Then, in 1820, Oersted in Denmark discovered that electric current in a wire produced a magnetic field encircling the wire, and soon thereafter Ampere in France was able to deduce the general relationship between electric current in a short element of wire and the magnetic field it produced at any distance and angle. Sturgeon made the first solenoid in 1823, and after a few improvements (such as the invention of electrical insulation, by the American Joseph Henry) it was possible to magnetize permanent magnets using electric current.

Permanent magnets made from steel require very little coercive force to magnetize, by comparison to today’s magnet materials. On the other hand, these materials are also very easily demagnetized, by shock, other magnets nearby, or even the effect of the Earth’s field, accidentally concentrated by steel objects. In 1932, Alnico was discovered, which is much more stable and also harder to magnetize. The magnetizing requirement was still not difficult to meet, however, by just using electric current off the lines and a solenoid, or a transformer to boost the current and a few turn of wire. Large “C” frame magnetizers using thousands of turns for each of two coils could magnetize assemblies on a conveyor belt. The same could be said of Cunife, a material which is rare but still occasionally used today, and various other types which are completely obsolete, such as Cunico and Lodex. With the development of Barium and Samarium ferrites, however, starting in 1952 (by Philips, in Holland) better magnetizing means were needed A half-cycle magnetizer connects the load fixture directly across the power line, turning on as the AC line voltage crosses zero, and then turns off again as it again crosses zero, one one-hundred-twentieth of a second later. Between these two times, the half-cycle machine may draw thousands of amps of current, directly from the line! Half-cycle magnetizers were made at GE by 1939. The first capacitive-discharge magnetizer seems to have been made by Dr. Weston (the founder of Weston Instruments) while at Radio Frequency Labs (RFL) in 1944. It was a very small unit the size of a large lunchbox, and was produced by RFL as the Model 107. It was used by the US Air Force to repair aircraft instruments. The shift from use of Alnico magnets to ferrite was greatly accelerated in 1978-79. A war took place in Zaire, which was a major supplier of cobalt at the time (Alnico contains about 30% cobalt).. This either forced, or provided the opportunity for (depending on one’s point of view) an increase in the cost of cobalt of about a factor of five. The huge price increase created great hardship for the users, even driving some of them out of business, and the survivors began an urgent search for replacement materials. Ceramic magnets have very different characteristics from Alnico, and the products usually had to be completely redesigned to use them. Most manufacturers who could changed to ferrites anyway, however, leading to a major and permanent loss of market share for Alnico.

These types require much more electronics than the earlier and simpler machines, but are far more powerful and efficient. The ignitron, a mercury-filled tube switch, invented about 1928, made these magnetizers possible. After the invention of the transistor in 1948 at Bell Labs, which is today's Lucent Technologies, solid-state devices became possible. The silicon control rectifier (SCR), invented in the early 1960's at GE, came to replace the ignitron, as it is much more reliable, repeatable, and efficient.

Rare -earth magnets, first pioneered in 1962 by Dr. Karl Strnat and others, required much higher magnetizing fields than the older materials. Nonetheless, relatively little development in magnetizing technology took place until 1990 or so. Since that time, however, new development began to accelerate. The situation today is mixed indeed, with some companies offering new designs, while others continue with equipment hardly improved in the last forty years or more. Improvements are certainly needed, as new magnet development continues at a high rate, and more powerful materials will certainly require better magnetizing methods. Ingenious engineers today are coming up with designs of magnetic devices which are at the very limits of the art to magnetize them, and sometimes beyond that art.

A number of companies manufactured magnetizing equipment Many years ago which no longer do so today. Shester, in Torrance, California, made small, tabletop magnetizers, some of which are still in service today. Your writer has examined many of them, as they are often in extreme need of repair, and no two units seem to have been made alike! F.W. Bell, a well-known manufacturer of hall-effect generators, gaussmeters, and related devices today once made magnetizers as well, but stopped in about 1984. Thomas and Skinner once manufactured a variety of magnetizers, conditioners, and other magnetics equipment. Accurate Electronics and Vast Electronics, both of Illinois, made equipment for magnetizing. Radio Frequency Labs later became RFL, then RFL Dowty, and was then finally sold to Magnetic Instrumentation Co. (MI). General Electric and Varian both once made magnetizers. Crucible Steel Company made magnetizers of the capacitive-discharge type for sale. Many companies simply made their own, as did Micropump in Concord, California, and Ted Davis Company in Oklahoma City, Oklahoma (sold to Vacuumschmeltze in about 1997). The Davis machines were about as good as any design on the market, at the time of their construction (about 1990). Magnetizer technology has advanced considerably since then, however.

3. Review of Magnetics, Electromagnetics

3.1 Basic Relationships

Oersted, in Denmark, discovered in 1820 that a magnetic field existed around a wire conducting electricity. Within a few months later, Ampere in France had extended Oersted's discovery to a complete description of a magnetic field produced at a distance and angle from an increment of wire carrying electrical current, which is, in modern vector terms

$$d\mathbf{H} = \frac{i}{4\pi} \frac{\left(d\mathbf{s} \times \mathbf{r}\right)}{r^3}$$

Where d**H** = increment of field (a vector)
d**s** = increment of conductor (a vector)
r = radius from the increment of conductor length to the field point (a vector)
r = radius from the increment of conductor length to the field point (a scalar length)

This equation is integrated to several useful relationships for coils in Section 6.

A few years later (1831), Michael Faraday discovered the relationship now called the Faraday Induction Law, that a changing magnetic field causes an electrical voltage, in a loop around the field flux ϕ (where $\phi = \int B \, dA$),

$$E = \frac{df}{dt}$$

These two together comprise the basis for electrical motors, generators, transformers, and many other devices on which almost the whole of modern technology depends.

The fundamental electrical relationships for passive circuit components are:

For resistors, Ohms Law:

$$E = ir$$

where E = voltage across the component,
i = electrical current, amperes
r = resistance, ohms

For capacitors,

$$E = \frac{1}{C}\int i \, dt$$

where C is the capacitance, Farads

and for inductances,

$$E = L\frac{di}{dt}$$

where L is the component inductance, Henrys

3.2 Eddy Currents

From Faraday's law, when magnetic flux changes (either increasing or decreasing) through an area an electrical voltage is developed along any loop around the area. This current creates a magnetic field of its own, in the direction to oppose the original change of field (note that it is only the change which is opposed, not the original field). Eddy currents may be useful (as in the "current mirror" strategy described later) but often they are harmful.

Eddy current problems may be solved by iterative methods, including all nonlinearities. Closed-form solutions exist, however, if the applied field is assumed to vary sinusoidally (that is, to be described by a sine wave) and if all the material properties are constants (such as permeability, electrical resistance, and frequency).

The solution of many useful eddy-current problems are given in references 1 and 2, in Section 12. They turn out to be functions of a parameter called the "skin depth" δ, which is:

$$d = \left[\frac{l n}{p m c}\right]^{1/2}$$

where λ = the wavelength of the electromagnetic wave, in free space

ν = the material resistivity
μ = the magnetic permeability of the material
c = the speed of light

In mixed, but more convenient US engineering units,

$$d = \frac{2.60\,inches}{\sqrt{f}}\left[\frac{n}{n_c}\,\frac{1}{m_r}\right]^{1/2}$$

where f = frequency (cycles per second, i. e. hertz)

ν / ν_c = material electrical resistivity, compared to copper

μ_r = relative permeability of the material, compared to free space

(Ref. 6, Section 6-4)

The skin depth represents the distance into a material that an electromagnetic wave would penetrate. Somewhat more accurately, one could say that the effect would be the same as the actual case if electrical currents were conducted across the skin depth at constant rate, unimpeded by self-generated magnetic fields, and then did not exist at all at greater depths.

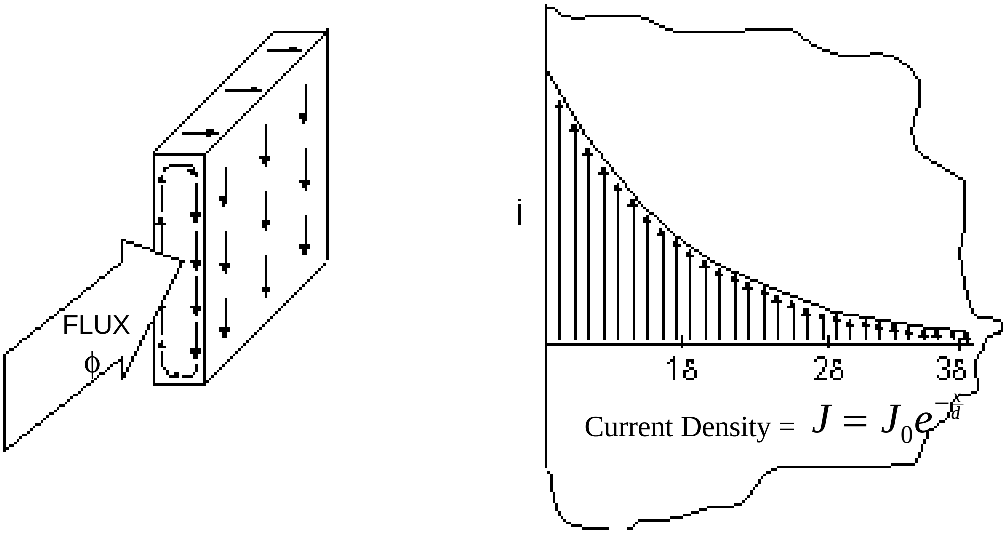


Figure 1. Eddy Currents in a Thin Lamination

When magnetic flux penetrates through a part which is tall (at right angles to the direction of flux) but narrow, electrical currents flow in opposite directions on the two sides of the part, as shown in figure 1 . A useful engineering approximation to the true solution is to note that, if the width is less than two skin depths, the currents in opposite sides interfere with each other, and so do not oppose the flux change. In fact, for such a plate of two skin depths thickness, only about 7% of the current flows compared to that which would flow in a very thick plate, and the eddy currents are nearly eliminated. The complete solutions are given in the cited references.

3.3 The Equivalence of Electricity and Magnetism

Please suppose that two people were by some means drifting in space, while still by the magic of imagination able to breathe, keep at a reasonable temperature, and function normally. Looking “up” (of course, there isn’t any up, but we’ll just use the phrase to define a direction), they observe a layer of electric charges, suspended in a plane at some fixed distance away. The charges are positive, and are distributed evenly in both directions in the plane, to infinity. Looking down they see a similar plane, of negative charges, a fixed distance below. Now if the two brave experimenters were to pull electrometers and gaussmeters from their pockets, they would not be surprised to discover that in the space they occupied, there was an electrostatic field of some number of volts per meter, but no magnetic field, as there were no magnetic sources present. They could easily have predicted what the reading would be, if they knew the charge distribution on the planes and the distance between them. Now let us suppose that one of them also has a small CO_2 fire extinguisher with him. He pulls the trigger for a second or two, which acting like a rocket engine gives him a small velocity relative to his associate, say one foot per second to the right. Now looking up, he sees the positive electric charge slipping off to his left, which constitute a sheet electric current. Looking down, he sees the same thing, but with negative electric charges, which is of course equivalent to a sheet of electric current moving in the opposite direction, that is to the right. It is easy to calculate that these two oppositely-directed electric current sheets must produce a magnetic field. If our observer were to check his gaussmeter, he would see that the field was indicated on it. On the other hand, his associate also has a gaussmeter, and if he were to glance over at it as he drifts slowly past, he will notice that it shows no magnetic field at all! The magnetic field exists by virtue of his velocity. If the same two experimenters were in a magnetic field instead, with no electric field present, and one of them acquired a small velocity, we know from the formula for back EMF that for him an electric field would appear, which his stationary friend would not experience. Electric and magnetic fields are in fact related through relativity, and change from one to the other even at ordinary speeds- there is no need to approach the speed of light, as is the case for many other relativistic effects.

4. Magnetic Materials

In magnetic materials, the individual atoms, or small groups of atoms which together act as one magnetic unit, may be thought of as comprising an interior structure (the nucleus, plus perhaps some electrons), around which one outer electron orbits. This single electron “looks” like an elemental electrical current loop. Just like a loop of electrical current, it produces a magnetic field (this very simple model, called the Bohr Magneton, is an oversimplification, but will serve the purpose). The effect is to produce a magnetic effect at a distance which is called a magnetic moment. As these atoms or atomic groups line up during formation of the material, they align themselves in the same direction over a small volume called a domain. This alignment minimizes their total energy. Once the domain grows to a certain size (and shape), however, the system energy may be reduced further if the atoms nearby align into another domain, with magnetic axis in a different direction. Each domain is a tiny magnet by itself, then, but its field is canceled out at a distance by that of other domains, so that the net effect at a distance is zero. In a magnetic material, when an exterior magnetic field is applied all the domains tend to align with it. Some domains align more easily than others, and so the resulting magnetic moment depends on how strong the applied field is, up until all the possible domains are aligned. We then say that the material is saturated. Further increases in coercive force caused by an exterior field only increase the magnetic field at the magnet by the same amount as the applied field, and the magnet itself does not add to it further. In a “soft” magnetic material, these domains are held in alignment only very weakly by so-called “pinning” forces within the material itself. If the exterior field is removed, thermal agitation of the individual atoms even at room temperature is enough to cause the domains to realign randomly, and the field breaks down. Even in materials in which the pinning forces are large, there is some temperature at which the alignment will collapse, called the Curie temperature. At lower temperatures, however, the domains of a strongly pinned material remain in place after alignment, producing a permanent magnet. The alignment can be reversed, in some or all of the domains, by again applying a magnetic field, this time in the reversed direction. For some materials, however, the virgin magnetization curve (that is, the curve of magnetization from the original, unmagnetized state) is different from that on subsequent remagnetization cycles. This is particularly true of some neodymium-iron products, for example.

It can be understood, therefore, that temperature has an effect on the magnetizing process. Increasing the temperature of a part may assist in magnetizing, if the rise is not too great, by helping to reduce the net pinning forces.

As the B-H magnetization curve, in two forms (the Normal curve, and the Intrinsic curve) is discussed in detail in the bound notes distributed with this class (Reference 7), it will not be repeated here. There is a variation of one part of the curve, however, which is of particular interest in magnetization (Percent B_r Versus H_s). An example of this curve is shown in Figure 2. It is the initial part of the magnetization curve, from H=0 to $H > H_{saturation}$, for virgin material, which results in positive B. The information is shown in intrinsic form, that is the part of the field caused by the exterior magnetizing field is subtracted out, and the magnetic flux density B is normalized to B_r, the remanent flux density for complete magnetization. This is the point where the B-H curve crosses the B axis (i.e. at H=0), after complete magnetization. Magnet manufacturers publish “recommended field to magnetize” values, but the value given usually will not completely magnetize the material. Their salesmen do not want this figure to be too high, as that would make their material less desirable to customers. From the (%Br Versus H_s) curve one can see the entire effect of peak field versus magnetizing field H_s. Some are perhaps understandably slow to give out the curve. On the other hand, some companies (such as Arnold Engineering, and a few others) freely offer this useful curve to their customers.

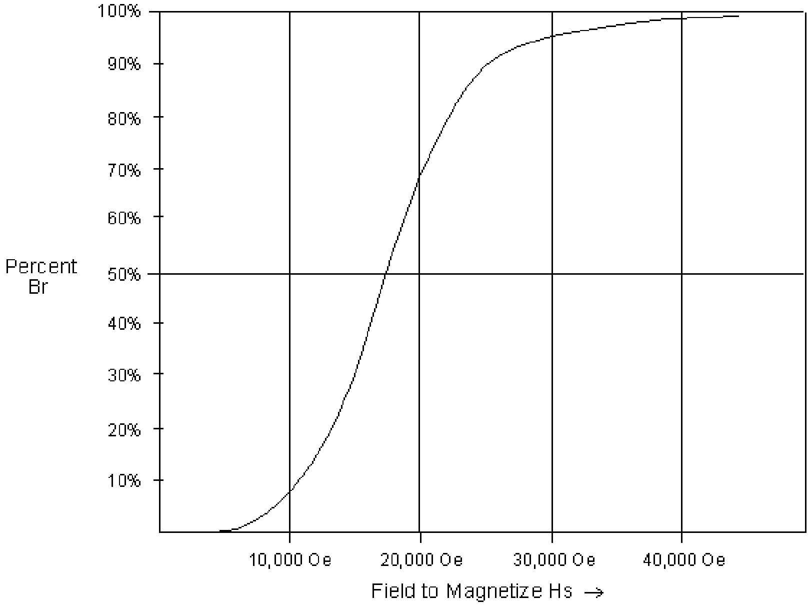


Figure 2. Typical Curve, %B_r vs. H_s for Neodymium-Iron-Boron

5. Pulse Analysis

All of the capacitive-discharge magnetizer circuits shown may be modeled as a series combination of a capacitor, a resistor, and an inductance. The electrical resistance must include the resistance of the source as well as that of the fixture (especially including the ESR, equivalent series resistance, of the capacitors), and also includes components from eddy-current conduction in surrounding structures, in the magnet itself, from "skin effect" in the conductors, etc. In addition, the resistance may increase during the period of the pulse (by perhaps 30%) due to heating in the fixture (the resistance of copper and most other metals increases with temperature). The inductance of a fixture containing steel pole material is dramatically affected by whether the fixture is below or above magnetic saturation (the inductance dropping greatly at currents above saturation). Other effects may be of importance too, such as the retention of energy by the electrolyte of the capacitors, the absorption of energy by the magnet, and other nonlinearities. Nonetheless, in many cases the overall system behavior of the magnetizer and fixture is modeled to sufficient accuracy by assuming constant values for the resistance, inductance, and capacitance. Even where the assumption of constant values of these parameters is not justified for final design, the linear analysis may provide a good first approximation and a check on the calculations. Where the linear approach using fixed values is not accurate enough, however, a computer simulation including all nonlinear effects may be used. The method is described in detail in the bound notes (reference 7).

6. Design of Fixtures

6.1 General

There are five types of conditions which must be met in the design of a magnetizing fixture:

(1) The fixture, in combination with the magnetizer, must provide a magnetic field of sufficient strength and in the proper direction to saturate the magnet. The directional requirement is usually not much of a problem in magnetizing anisotropic materials, which can only be magnetized along a particular directional line (although with either sense, i. e. from right to left, or from left to right, along that line). This is because the field component in the required direction varies as the cosine of the angle between the two, which does not change much for angles up to ten degrees of arc or so. If the material is isotropic, however, meaning that it can be magnetized in any direction, the direction of field may be of much greater concern.

The magnet domains themselves align in a very short time (on the order of 10^{-8} to 10^{-9} seconds). The field may have to be maintained for a significantly longer time, however, in order to overcome electrical eddy currents, which may occur in the fixture, the magnet itself, or in associated structure.

(2) The part must be held in the fixture in the proper orientation, accurately but without imposing stresses on the part during magnetizing (and possible thermal cycling as well) without breaking it. The part must also not be damaged, chipped, or broken as it is being removed from the fixture, or as it is loaded.

(3) The windings must be strong enough, or must be reinforced to be strong enough, to withstand the mechanical forces on them during the magnetizing pulse, either to fail due to ultimate stress limits or, at a much lower level, in fatigue (after a number of cycles). Fields high enough to magnetize high-energy magnets often cause forces which could pull apart copper conductors in a single pulse, if they are not strengthened by other means. These forces are also more than strong enough to bend, crush, or extrude out epoxy potting plastics.

(4) The thermal requirements must be met. the near-instantaneous temperature rise in the windings during the pulse occurs too quickly for much of the heat to escape across even a single thin layer of electrical insulation. If this rise is too great, the insulation will fail, on a single pulse. A thermal time constant exists for this effect, and a thermal mass, which is often significantly different from that of the fixture as a whole (that is, the time constant is shorter than that of the fixture, and the mass is less). Both must be taken into account. An extreme example is a large "C" frame fixture, used for automatically

magnetizing parts carried on a conveyor belt A fixture of this type may weigh more than a thousand pounds and, if air-cooled, may have a time constant of four hours or more.

(5) The fixture must also protect the operator and nearby equipment from possible accidental effects of the magnetizing operation. Magnets sometimes have internal weaknesses not visible on the surface. Under the stress of magnetization, they shatter or lose pieces from the surface, which may be ejected violently. Magnet parts, or stray metal such as nuts, etc. should not become dangerous projectiles. If the winding should fail, the fixture shell, if conductive, must not be an electrical hazard. The fixture should not become hot enough to accidentally burn the operator, or adversely affect the magnet. Stray magnetic fields around the magnetizer in operation should not attract metal objects, or be hazardous for the operator or others in the vicinity.

The field strength at a distance from an increment of conductor carrying electrical current is described by Ampere's Rule. If a wire is wrapped into a loop of radius r (with a cross-section across one side of the loop small compared to the loop itself), the field on the axis, the field at a distance x from the coil center is:

$$H = \frac{ir^2}{2\left(r^2 + x^2\right)^{3/2}}$$

The units are in SI (Systeme International) metric. In all these, it may be useful to use the units conversion: one amp-turn per inch = 2.0213 oersteds

For a uniformly-wound thin-walled cylindrical coil, of turns n, radius r, and carrying current i, the field on the axis
is in the axial direction, and is of strength:

$$H = \frac{ni}{2}\left(\cos\theta_1 - \cos\theta_2\right)$$

Where θ_1 and θ_2 are the angles between the axis and lines from the point on the axis at which the field is located to the outer ends of the coil. When the point is inside the coil, one of these angles exceeds 90°, and so the cosine is negative. When the point is outside, both terms have the same sign. The variation of axial field strength versus position on the axis for a coil of diameter equal to its length is shown in figure 3.

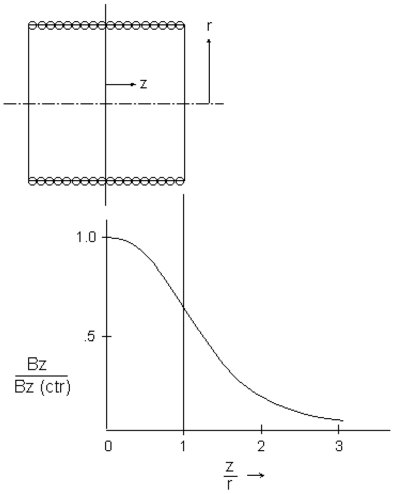


Figure 3. Axial Magnetic Field in a Coil of Diameter Equal to Length

The field across the solenoid internal volume, however, is different from that on the axis (it is greater). Since in a magnetizing fixture the field must equal or exceed the value to magnetize everywhere, if the field varies over the useful volume then considerable energy is wasted by over-magnetizing some of the volume. The energy is proportional to the square of the field strength, so for example a 20% excess requires about 44% more energy. The differences, if uncorrected, are often larger than that.

If one considers LaPlace’s Equation, which any magnetic field in space must satisfy, which in cylindrical coordinates is:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 V}{\partial a^2}+\frac{\partial^2 V}{\partial z^2}=0$$

where the radius from the axis is r, the angle around the axis is α, the distance along the axis is z, and V is a scalar potential such that its partial derivative in any direction is he component of magnetic field in that direction. If the coil is axially symmetric, the second term is zero. If we could make the axial variation of the magnetic field zero, the last term must vanish also, and so it can be seen that the first term then must be zero, and so the field is uniform across the diameter, as well as along the axis. In fact, we can make this happen for a considerable part of the volume inside the solenoid, by using a non-uniform winding, increasing the number of turns per length towards the ends. This results in a higher (minimum) magnetizing field for the same amount of energy.

When the coil is pulsed, stresses are developed on the coil tending to crush the coil in from the ends, while at the same time expanding the coil in diameter. These are called Maxwell stresses, and may be computed from:

$$S=\frac{force}{area}=.571\times10^{-6}\ B^2\ \frac{lbf}{gauss^2\ in.^2}$$

For example, at 35,000 gauss, the force on the cross-section of a fixture would be 699.5 lb / in^2. If that stress occurred uniformly across a coil 6 in. across, and if the copper comprising the turns had an area of .20 inches^2 per side and inch of length , then the hoop stress across the coil would be 10,493 psi. This is less than the ultimate strength of the copper, but more than it’s fatigue strength, and so the coil would work at first but eventually fail.

If we strengthen the coil, to prevent its failure, we must use some material to do it, outside the windings. Then, however, heat generated in the coils will be trapped inside by whatever material was used to strengthen the coil, as it will have to pass through it in the radial direction. If cooling coils are placed between the coil and the reinforcement, the coils will be in danger of being crushed by the magnetic forces of coil expansion. It seems that we can either have a fast-cooling coil, or a strong coil, but not both.

6.2 “Supercoil” Construction

Oersted has recently obtained a patent on a way around this dilemma, resulting in a coil which is both strong and cools quickly. The arrangement is shown schematically in figure 4. Separate coils are wound in pairs, using a conductor which is thin in the radial direction (making it easy to form) but wider in the axial direction. The conductor is given a “jog” in the center of one conductor width, and then each end is wound to form a flat coil pair. The number of turns of each coil pair is varied so that the final coil will have a nearly uniform field over the useful volume. Cooling coils or other cooling means are made into thin flat disks which are insulated, and inserted between the coil pairs. The coil pairs may now be reinforced on the outer diameter for strength. The heat travels easily through the copper, crosses only one insulation barrier (which has far less thermal resistance then, say, a coil of the same number of turns of round wire), and into the coils, where it is carried off. The expansion stresses, on the other hand, are in a different direction, and so the reinforcing jacket does not interfere with cooling.

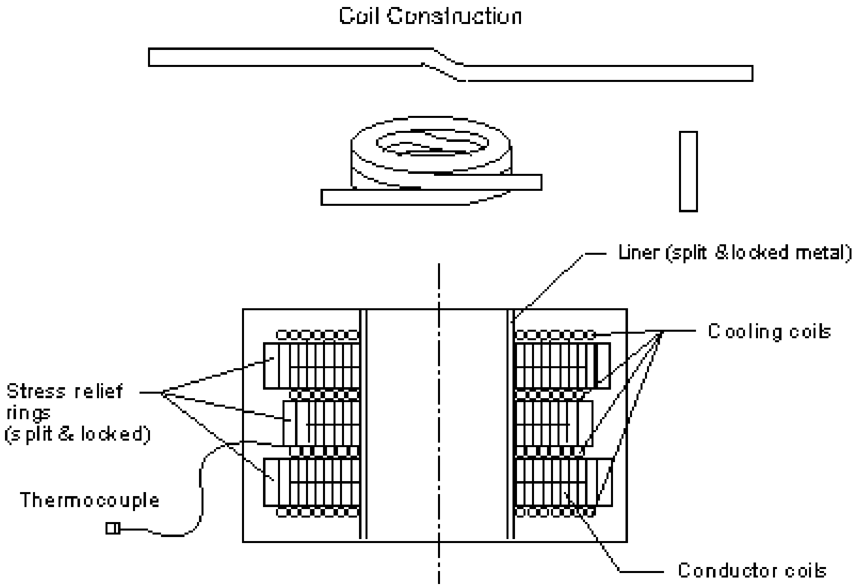


Figure 4. “Supercoil” Fixture

6.3 Bitter Coil

A coil construction discovered by Dr. Francis Bitter, and originally used to produce extremely high magnetic fields in coils operated with DC current, is known as the Bitter Coil (figure 5). This construction has been adapted for magnetizing with air cooling, and is particularly popular among European manufacturers. Sheets of conductive material (almost always copper) are cut with a pattern which forces electric current to travel along the inner edge, around the circular hole within which is the magnetizing volume. Each sheet represents about ¾turn of the coil. The coil sheets are then connected to each other in stacks, with conductive spacers to separate the sheets at the ends, and thus from one sheet to another. The other spacers are non-conductive. The remaining sheet metal around each conductive path acts as a thermally-conductive fin, with a surface area much larger than a wire of comparable size would have. If air is then blown across the sheets, heat is transferred to the air for cooling. Air cooling is relatively simple, inexpensive, and will not conduct electricity in case of failure, and there is no electrical insulation between the metal and the air, which would reduce heat transfer. The idea works well under some conditions, but is not without limitations. The original Bitter coil design was made to be driven by huge, special generators, with DC current, not a sharp pulse. In order to make the plates stiff enough, there are a limited number of sheets, and thus turns per length. To get the necessary coercivity, therefore, the current must be very high. In turn, to avoid overheating, the pulse must be very short. Forces between the plates is high, and they may buckle if not sufficiently stiff. The fast pulse required may result in eddy-current problems in the magnet or structure, and the high current increases the cost of the magnetizer and stress on the components. Bitter coils do not cool a fast as a comparable fluid-cooled fixture used with a chiller.

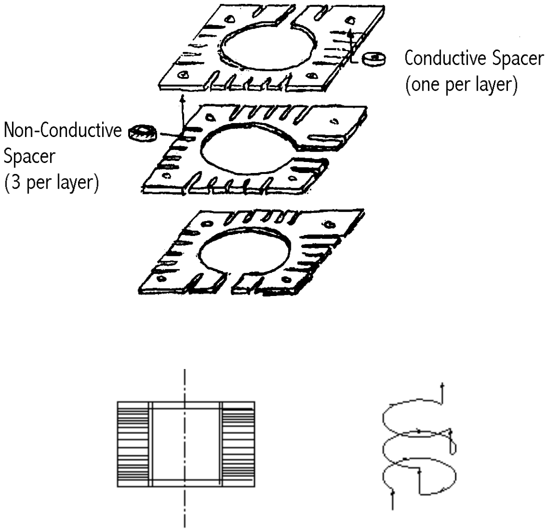


Figure 5. Bitter Coil

6.4 Vortex Tubes

Air from a compressed air source may be chilled to a very low temperature by a strange and simple device called a vortex tube. The tube, which is small and has no moving parts, accepts air at high velocity at a location in the middle of the tube length, swirls it internally from its own velocity at a high rate of rotation, and separates the stream into two parts, which come out the ends. One of these streams is hot, while the other is very cold! The process is very inefficient, and is noisy, but it is simple and effective. When using a vortex tube to cool a magnetizing fixture, one must avoid leaving it on when the fixture is cold, as the low temperature may cause water to condense inside the fixture.

6.5 Miscellaneous Other Topics

The internal heating caused in magnetizing fixtures may cause problems with the liner to the magnetizing space. If plastics are used, they may form blisters, which expand inward, reducing the useful volume. If metal liners are used, they may conduct significant eddy currents, with both heating and reduction of the field available for magnetization. At Oersted, we use metal liners which have nonconductive slits in them, which prevents circular electric currents.

An idea which this writer calls, for lack of a better name, a “current mirror” has sometimes been useful. If a massive part of copper or another good conductor is introduced into a rapidly pulsed field, eddy currents are induced in the part which prevents the field from penetrating it. It is as if the coils producing the field were “reflected” in the massive conductor, as if in a mirror, so that the current shown in the mirror produced a field which just forced the resulting flux lines from the original field to run parallel to the conductive part.

6.6 Magnetizing of Radially-Oriented, Single Pole-Pair Rings

Rings of this type, with for example a South pole over the entire inside surface and a North pole on the outside, are used in linear actuators an certain types of speakers. Since flux lines must close on themselves, all the flux passing through a magnet wall in the radial direction must also pass through one of the ends. The area of the side wall is:

$$A_{side} = 2prl$$

where the magnet axial length is l and the radius is r.

The area of each end is :

$$A_{end} = pr^2$$

If the average flux density is to be the same at the ends (of which there are two) as at the sides, then:

$$A_{side} = 2\ A_{end} = 2prl = pr^2$$

or

$$l = r$$

If the magnetic flux density needed to magnetize the part is very high, such as for neodymium-iron, then it will be very difficult or impossible to magnetize the part completely and evenly if the length of each ring is longer than one radius. The flux density at the ends becomes higher than that in the walls, and the energy, increasing as the square of this field times the volume, becomes very high.

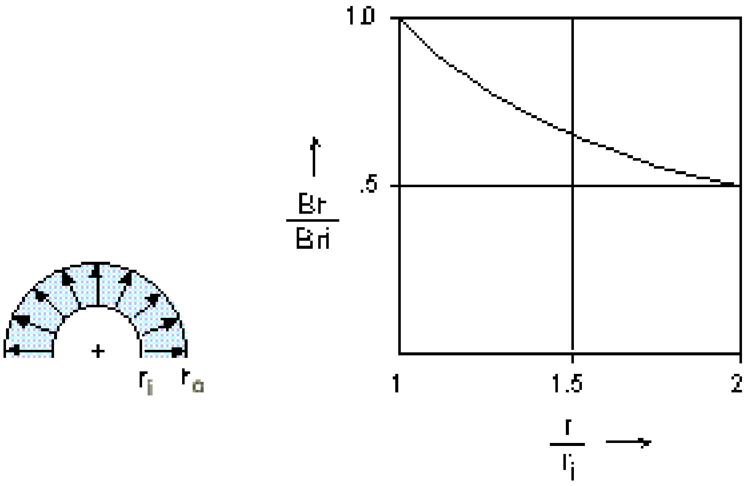


Figure 6. Radial Flux Density Br vs. Radius in a Thick-walled Radially-oriented Magnet

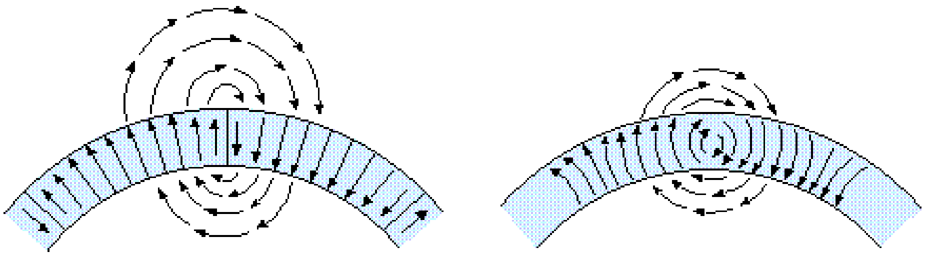
A thick-walled cylinder is shown in figure 6. A thick-walled ring of material requiring a high field to saturate is even more difficult to magnetize. Flux radiating outward from the center must have a higher flux density at the inside edge of the ring than at the outer edge, and in fact the flux density is just inversely proportional to radius. As a given minimum flux density is required everywhere, the flux density must be greater than this minimum at the inside edge. If the ratio of outer diameter to inner diameter is large, much more energy is needed at the inside, and the task may become impossible. Instead, if such a thick-walled ring is really needed, it may have to be magnetized in two or more nesting sleeves. It can be seen that this also reduces the length of ring which can be magnetized effectively.

6.7 Multipole Patterns

When two poles are magnetized into one surface side-by-side, some imagine that the fields at the surface will show full strength over one pole, then abruptly switch to full strength in the other direction, with a very narrow transition region. This opinion is strengthened by viewing such a transition through plastic magnetic viewing film, which might perhaps show a very narrow line of a light color, flanked on each side by black regions indicating poles. The construction of this film is described in the notes supplied with the seminar, and will not be repeated here. The film switches color with a field difference of only about 50 gauss, however, and so the actual transition (which might be, for example, from +4000 gauss to – 4000 gauss) is actually much wider. In fact, it is impossible to obtain a transition which is much narrower than the part thickness- even two separate, perfectly magnetized parts when brought together have a transition region between them which is about 1.4 times the thickness of the magnets. This comes about because the opposing fields of the two parts tend to cancel each other in the transition region.

It is impossible to produce a magnetizing field which sharply reverses, although the transition region can be reduced by increasing the field considerably over that needed to saturate (if this is possible). If because of difficulties such as winding thickness, insulation, and pole saturation, it is found that two adjacent poles have an excessively wide transition region between them, it can be reduced by moving the part to one side a distance of part of the transition width and magnetizing the part again in this new position. This method has been used sharpen the transitions of swing-arm actuator magnets used in computer hard drives, for example, for about a decade.

A metal alloy often known as Vanadium-permandur (certain companies have trade names for it which are different, however) has a significantly higher saturation flux density than does iron or steel. Low carbon steel saturates at about 20,500 gauss, whereas the saturation flux density of vanadium-permandur is about 23,000 gauss. The material is available in thin sheet of various thicknesses, useful for laminations (to suppress eddy currents) in critical regions of a magnetizer. It is, however, very expensive, and often difficult to obtain in small quantities.



Radially-oriented multipole ring in air

"Circularly" magnetized isotropic multipole ring in air

Figure 7. "Circular" Pole Transitions

6.8 "Circular" Magnetization

Anisotropic magnetic material may only be magnetized along one directional line in space. Isotropic material, on the other hand, may be magnetized in any direction. Isotropic material is much less strong, in terms of energy product, than the oriented (anisotropic) variety. When magnets are used in magnetic clutches, as for example an outer ring which will not be used with a backing ring, and when the material is isotropic, it may be advantageous to use a magnetizing pattern which your writer has called, for lack of knowledge of a better name, "circular magnetization". This method is shown schematically in figure 7. For anisotropic, radially-oriented material, the coercive force of the magnet must cross through the radius only. If no backing ring is present, the flux must link through space outside the ring. In a circular pattern, on the other hand, the flux travels approximately in a half-circle entirely within the ring. Very little flux leaves the ring, as leakage flux. The longer path within the ring makes better use of the available material, particularly that which would have been in the pole transition region, and its increased length results in a higher magnetomotive force (mmf) than would be the case for a radial path. As a result, magnets magnetized in a circular pattern, of isotropic material, sometimes produce as high or even higher flux density in the gap under the ring than would a much stronger, radially-oriented material. In order to produce such a pattern, an outer “current mirror” ring may be helpful to better curve the magnetizing flux field.

7. Magnetizers

7.1. Non-electronic Means

Magnets may sometimes be magnetized by non-electrical means. For example, flexible bonded ferrite sheet, often referred-to as Plastiform, is sometimes magnetized in production this way (please note that Plastiform is, in fact, a registered trademark, but it was the name used for it by 3M during early sales of the product, and so it has become almost a generic name).

As this sheet is often used to adhere to thin steel sheet metal, it must be magnetized in narrow strips to avoid saturating the backing material. The thickness is usually not great, and the required coercive force to magnetize is only 10,000 oe or less. Fields of this strength may be generated without too much difficulty using either Alnico or rare-earth permanent magnets, along with steel poles to concentrate the magnetic flux. Alnico is also occasionally magnetized using a permanent-magnet generated magnetic field. As the magnetic flux must be high, compared to the coercive force requirement, steel poles for flux concentration along with the smallest remaining air gap possible (after the part to be magnetized is in place) are usually needed.

7.2 Electrical Means

7.2.1. Components

7.2.1.1 General

In order to discuss electrical means of magnetization, we need to consider the properties of some electrical components before the various circuits using them may be addressed. At ordinary voltage and current, we may simply turn a circuit on and off using a mechanical switch to open or close the line, and the needed current may be drawn directly from the power line. The situation is very different at the levels of voltage and current needed to generate fields strong enough to magnetize modern magnet materials, however. First, the current density needed is so high that the conductors would almost immediately overheat, or even vaporize, if left on for more than a few milliseconds, because of the resistance of the conductors themselves. Next, the current causes such high mechanical forces, due to its associated magnetic field, that mechanical devices such as switches would actually be torn apart by them. Besides these, the voltages needed are so high that it is difficult to keep the current from arcing over nearby uninsulated contacts, and the combination of heat and voltage may destroy electrical insulation.

7.2.1.2. Switches

7.2.1.2.1 General

Certain types of electronic switches exist which are capable of handling the very high voltages and currents need for magnetizing pulses. Transistors, and the earlier vacuum tubes, are capable of controlling electrical current at any desired rate, but only up to current levels far below those needed for magnetizing. Devices such as MOSFETs (Metal Oxide Semiconductor Field-Effect Transistors) can both turn on, and then turn off, sizeable currents, although they may overheat if operated at intermediate states, that is, say half-way on. They are still unable to handle the really large currents needed for magnetizing, however, except in very special circumstances. Two control devices, or electronic switches, exist which are able to handle such currents, with some limitations. When off, they can block large voltages. When triggered, they turn on completely, and cannot be used to control the current at some intermediate state. Once they turn on, in fact, they cannot be turned off at all. The only way to stop the current is to reduce the current through the switch to near zero (the holding current of the device) by some other means momentarily, or by reversing current direction through them. When this happens, they reset themselves to their original, blocking condition.

7.2.1.2.2 Ignitrons

The first of these is the ignitron (ig-NIGHT-ron). People who have only encountered the name in written form tend to pronounce it " IG-nat-tron", but those making the tubes use the other form, meaning by it that the current of the gate electrode "ignites" the mercury in the tube, to cause the main circuit to conduct. These are large glass vacuum tubes, usually with metal jackets, having three contacts. The top and bottom electrodes are for the main circuit, and the third is the gate. To fire the tube, a pulse of electrical current is passed into it to the base (cathode), with the gate positive. Considerable power is needed, as the gate touches a pool of mercury in the tube, vaporizing enough of it that the gas completes the circuit from the positive anode (the main circuit) to the base (anode). Once conduction starts, it is rapidly self-propagating, vaporizing more mercury until the tube is in the completely on state. Although ignitrons are rugged and capable of handling high currents, they have some serious drawbacks:

(1) The generate considerable heat, and often require water-cooling (the tubes are built with a water jacket and fluid lines).

(2) The voltage drop across them is high and variable (typically 30V-200V). A cold tube has a higher voltage drop, which reduces as the tube heats up in use.

(3) The voltage drop across the tube increases with age, and eventually the tube is no longer useful without repair. At one time, there were several repair facilities in the US where tubes could be refurbished, but to the best of my knowledge they have all been closed because of government concerns for environmental safety.

(4) They are relatively expensive

(5) Considerable power is required to trigger them

(6) They may be harmed if tipped from the vertical direction, and must be stored ,shipped, and operated in this position.

In addition to these, your writer has sometimes wondered what would happen if an ignitron tube wall broke while in operation. Mercury vapor is extremely poisonous. He has never heard of a case in which this has happened, however. Nonetheless, the juxtaposition of hot glass, cold cooling liquids, and large mechanical shocks, along with high voltage and electrical current, seem to be good reasons for caution.

Although ignitrons do not conduct continuously in the reverse direction, they may not cut off sharply, but rather conduct for a short time in the opposite direction before shutting down if the voltage across the tube is reversed. A reversal of current in a magnetizer coil, however, even at a reduced level and for a short time, may lead to partial demagnetization, and cannot be permitted.

7.2.1.2.3 Silicon Control Rectifiers (SCRs)

The second type of switch, invented more recently, is the SCR (Silicon Control Rectifier). The SCR is a four-layer solid-state device. The voltage drop across an SCR is small (about half a volt at low current, and perhaps 1 volt at full conduction) and repeatable, and does not vary significantly with temperature, use, etc. The power required to trigger it on is very small, compared to the ignitron. Fluid cooling is usually not required. For the same power rating, an SCR is much smaller than an ignitron, and of course it does not contain mercury. It may be shipped and used in any position. Like ignitrons, however, an SCR is either on or off, and will not remain in an intermediate state. Once it is turned on, it can only be turned off again by dropping the current below the holding current limit, which is comparatively small. For example, one SCR known to the writer capable of carrying momentary pulses of current of up to 35,000 amps has a holding current of less than 150 milliamps.

7.2.1.3 Diodes

A diode is a two-terminal electronic component which allows electric current to pas in one direction freely, but blocks current in the reverse direction. Current is allowed to flow from the anode, or positive, terminal, to the cathode, or negative terminal, but not in the other direction. Semiconductor diodes are now available which allow very high currents to flow with negligible voltage drop (.4 to 1 V., depending on current, is typical), which shut off very quickly on reversed voltage, and which can block very high reverse voltages. This was not always the case. In addition, they are relatively inexpensive, compared to other devices of similar current and voltage ratings.

7.2.1.4 Capacitors

Capacitors store electrical current and power until required. Two main types are used in magnetizing circuits, unipolar and bipolar. Unipolar capacitors may only be safely charged with one polarity (the positive terminal must be at positive voltage, or zero, relative to the negative terminal), whereas bipolar capacitors may be safely charged in either direction.

Most magnetizing circuits, at least in the US, use aluminum electrolytic capacitors, which are unipolar. These capacitors are much less expensive, and store much more energy per unit volume, than other types. They cannot accept more than about one volt in the reversed direction, however, without suffering catastrophic failure. A modified form, called “military”, however, may take several volts more in reverse before failure. The best large capacitors of this type are useable up to about 450 V. (with occasional surges to 500-550 V.). In addition to capacitance, these capacitors have internal resistance, called ESR (equivalent series resistance). Since they are made of a spirally-wound foil sheet, they have internal turns which the stored current must negotiate on the way in and out, and therefore some inductance as well. When these are combined, as they are in operation in a magnetizer, the capacitors have an impedance which is a function of rate-of-change of current, or frequency. A typical plot of impedance versus frequency for an aluminum electrolytic capacitor is shown in figure 8. It can be seen to be higher at very low frequency, drops down at intermediate frequencies, and then rises again at higher ones. Typical operation of these capacitors, however, especially for use in magnetizers, is in the middle, where the impedance is lowest.

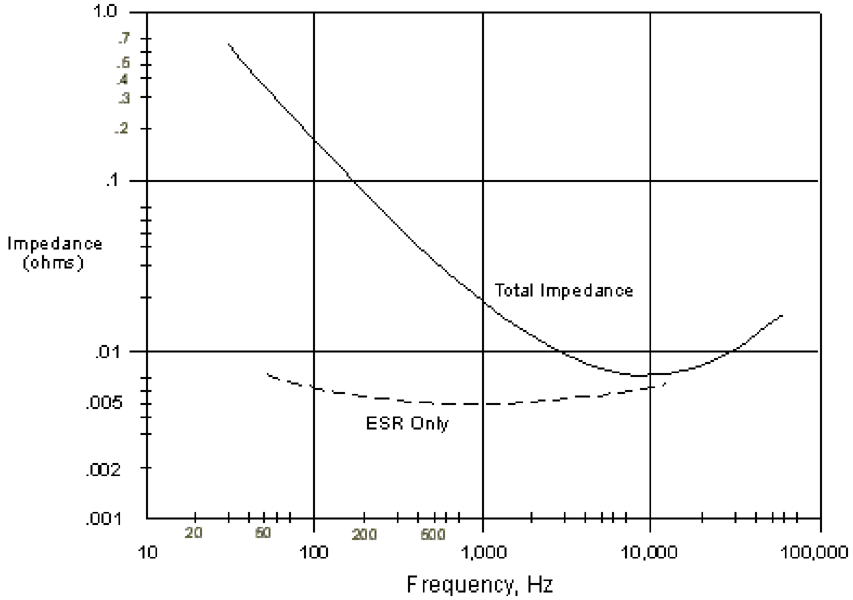


Figure 8. Impedance vs. Frequency, Large Electrolytic Capacitor

Although these capacitors operate at perhaps a maximum of 500 volts or so per capacitor, they may be combined in series to allow use at higher voltages. When two similar capacitors are connected together in series, the pair has half the capacitance of the individual unit, twice the ESR or internal resistance, and twice the voltage. The stored energy, however, is unchanged, which is:

$$U_c = \frac{1}{2} C E^2$$

where U_c = stored energy (Joules)

C = capacitance (Farads)

E = charging voltage (Volts)

As the resistance increases with more capacitors in series, while the capacitance is less, there is a practical limit at which the internal resistance of the capacitor set is large enough to absorb most of the discharge energy, instead of delivering it to the fixture. It is found that two such capacitors in series is usually acceptable. A larger number, however, may not help and may even harm overall performance of the magnetizer – increased number of series capacitors allow higher voltage, but may actually result in lower peak current. Whether it is harmful or not depends on the resistance of the fixture, compared to that of the capacitor banks, and no general assessment can be made for all cases.

Another characteristic of the aluminum electrolytic capacitor is that much of the energy is stored in the dielectric material used between the foil layers, which is usually an oil-like liquid. When the capacitor is discharged quickly, as in a magnetizing pulse, a small amount of the energy does not come out of the dielectric immediately, but may take several seconds to emerge completely. If the pulse is very fast, the capacitors may be discharged to zero, but then (with the discharge circuit reset to off) they may partially recharge themselves, with no applied power! The amount of energy involved is fairly small, but it can be seen in he above formula that the energy is proportional to the square of the voltage. If only 1 percent of the energy remains in the dielectric, therefore, the voltage could rise to 10 percent of the charge voltage, or 40 V. for a pulse charge of 400 V, per capacitor, for a total of 80 V! This would be unusually high, but a remaining (actually, recharged) voltage on such a pair of electrolytic capacitors of 10V-50V. is often observed.

Bipolar capacitors may be made by a number of constructions, such as oil-filled, mica, foil-paper and foil-plastic (such as Mylar or polypropylene). Typically, in comparison to aluminum electrolytics, they have much higher operating voltages, much lower ESRs (resistance), may often be used at higher currents, and of course may be charged in either direction, which makes it possible to use them in some circuits for which the electrolytics are unsuitable. However, for a given amount of stored energy, which is a basic measurement of the value of a capacitor in a magnetizing circuit, the bipolar capacitor may take up ten times the space, and cost twenty times as much, or more. As the cost of the capacitors is the largest single item in the parts cost of magnetizers, this has a very serious effect on overall cost.

7.2.2 Circuits

7.2.2.1 DC Coils

Coils using direct current may be used for generating high magnetic fields, although the method is inefficient if only a momentary field is needed, a great deal of power is required, and cooling is often a problem. Using huge special DC generators, DC coils have been operated at field strengths of over 200,00 oersteds, at the Francis Bitter National Laboratory. Such means are impossible to use in production, of course. using a steel yoke as a flux-return path and large coils with thousands of turns on steel cores facing a gap, fields of up to 14,000 oe or perhaps more are obtainable without special cooling, and using liquid cooling plus a limited time of operation, field strengths of up to 100,000 oe are attainable, for a simple axial cylindrical field shape. Some additional degree of flux concentration is possible using Vanadium-permandur pole faces, which saturate at a higher field than does steel (about 24,000 gauss, versus 20,500 gauss for steel). Such equipment is both expensive and inefficient (although much less so than that required for the National Labs experiments), and requires considerable power, although it may be obtained from industrial power lines. Yokes with DC coils are sometimes used to magnetize even high-energy materials, although the practice is not common because of expense.

7.2.2.2 Half-Cycle Magnetizers

A half-cycle magnetizer is shown schematically in figure 9. The design of these devices is very old, going back to before WWII, and well before the discovery of semiconductors, and the usual designs reflected some of the difficulties associated with the components available at the time. An ignitron mercury-filled tube is connected in series with an output transformer, directly across one phase of the power line. During some point in the positive voltage half-cycle of the line, the ignitron is triggered on. For the next partial cycle, until the voltage passes through zero and reverses enough to stop the current through the transformer, it is connected, very nearly as a short-circuit, directly across the line. During the partial cycle, thousands of amps of current are drawn from the line. This of course has a very violent effect on the line, and is perhaps similar to a lightning strike. Other equipment, possibly at other locations connected to the same line, may experience great electrical surges, and possibly fail. The pulse is so extreme that conventional power meters, which are electromechanical in nature, cannot respond fast enough to record it, and so the user may not have to pay for the power drawn.

The ignitron switch allows considerable reverse current to flow before it shuts off. If such a reversed current were allowed to flow in the fixture, the part would first be magnetized in the intended direction, but then an instant later be partially demagnetized by the reversed current. A good diode could prevent this, but at the time such diodes did not exist. The solution was to use an output transformer. Before the forward pulse occurs, a DC current is applied to the transformer in the reverse direction, almost to saturation of the core steel in the transformer. The circuit to do this is called the “premagnetize circuit”. Now when the forward pulse is applied, it is transmitted to the output winding (which depends only on rate-of-change of current, not its absolute value), but a following reversed current saturates the transformer core and so is not significantly transmitted through to the output. The transformer thus takes the place of a rectifier. In addition, the line side of the transformer may have more turns than the output side, so that the output current may be higher than that of the line (at lower voltage, of course).

It is perhaps surprising, but not only are such magnetizers still in use in a few places, but they are still being quietly sold as new equipment! A half-cycle magnetizer is less expensive than some others, and has limited but possibly acceptable performance. On the other hand, the user faces possible consequences, such as destruction of other electrical and electronic equipment.

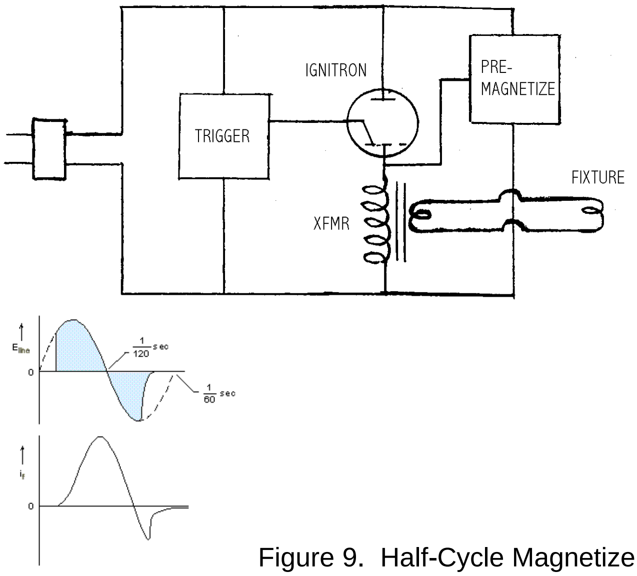


Figure 9. Half-Cycle Magnetizer (ca. 1939)

7.2.2.3 High-Inductance "C" Frame Magnetizers

A "C" frame refers to the shape of a large laminated steel frame, made in the form of the letter "C", with a horizontal gap and a flux return path through the steel. Very large coils, consisting of thousands of turns each, are placed on either side of the gap, and are connected in series, as shown in figure 10. When a switch is closed, current from the line is rectified in a bridge rectifier and passed to the coil. The circuit shown is single-phase, but a three-phase arrangement using a different rectifier arrangement works as well. The inductance of the fixture is very large, perhaps on the order of ten henries or more, and so the current builds up slowly, over many cycles. The buildup may take as long as a second or so to reach the required current, resulting in the rated field in the gap. When the field is large enough, which is often determined by a timer, the switch is closed again. The large amount of energy stored in the magnetic field of the gap causes current to continue to flow in the pulsed-DC side of the circuit, however, until the energy is dissipated in the coil winding resistance. Current decay may take place over an additional second, after the switch is closed. This type of magnetizer was formerly favored by many in the speaker industry, but is now being gradually replaced by capacitive-discharge machines. The "C" frame magnetizer produced good results with older speaker designs using embedded Alnico magnets (the surrounding structure acting as a flux-concentrator). It could later be used with ferrite-based speakers also, although the magnets are often not completely saturated (typical units producing on the order of 7000 oe-9000 oe at the magnet, which may take about 10,000 oe to saturate). This type of magnetizer has almost no effect at all on the latest rare-earth materials, however.

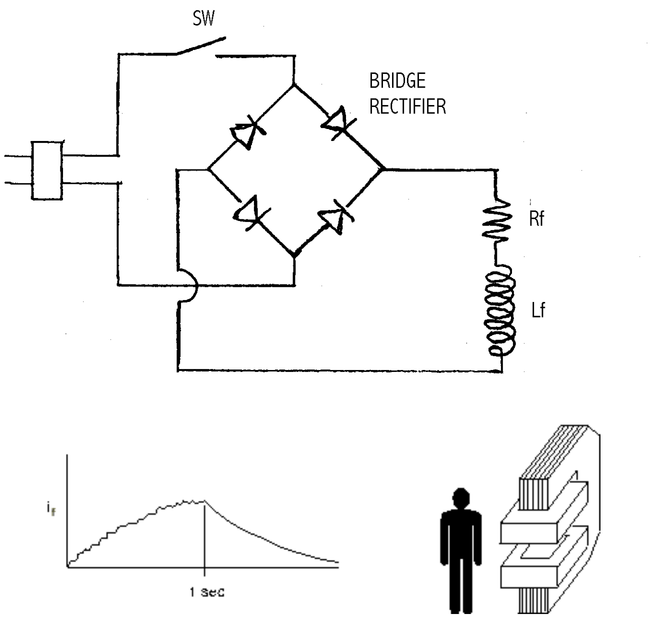


Figure 10. "C" frame Long-Cycle Magnetizer

As a typical example, a high-inductance "C" frame magnetizer might have a gap which is 8 inches wide by 8 inches deep, across the cross-section of the steel, and the gap might be 7 inches wide. The coils would extend out a considerable distance from the steel core, and be two feet or so across on the outside. A three-phase line of 480 VAC might power it, drawing a maximum of 60 amps. The "C" frame has a very large thermal mass, and so the temperature slowly builds up during the production run. If not water-cooled, however, the duty-cycle might be limited to possibly 4 hours, whereupon the device is allowed to cool until the next day. A magnetizer of this type draws considerable power, many times that of a capacitive-discharge type of the same magnetizing capacity.

7.2.2.4 Capacitive-Discharge Magnetizers

7.2.2.4.1 General

A capacitive-discharge magnetizer is a device which accepts electrical power from the line, usually boosting it in voltage in the process, and stores it in large capacitor banks. When enough energy is stored, and a part to be magnetized is in place in the fixture, a switch (almost always an ignitron or SCR) is closed, and the energy is allowed to flow in a fast pulse through the fixture. The fixture is designed to transform as much of the electrical energy as possible into a momentary magnetic pulse, usually of only a few milliseconds or less in duration, which coerces the magnet into the desired magnetic state.

Magnetizers of his type may generally be classified as being of low, medium, or high voltage. Please note, however, that this classification is my own, and that there is no generally agreed-upon classification of this sort. The divisions are somewhat arbitrary, but come about from the limitations of the aluminum electrolytic capacitor. Low voltage, then would mean a magnetizer in which all the capacitors of this type could be in parallel, which is limited to about 450-500 volts. Medium voltage, which describes many magnetizers currently in use, would those which could be made with capacitors in pairs, or up to perhaps 800-1000 volts. High-voltage magnetizers are usually made of non-electrolytic capacitors, and often range from perhaps 1500 V. up to 3000 V. or more. For reasons of economic design, the high-voltage magnetizers usually are used to produce shorter pulses (i.e. higher frequency) than those of the other two types. The reduced pulse time is more efficient in converting the electrical energy to magnetic energy, but may result in eddy-currents in the part, preventing the field from penetrating all the way through it and leading to incomplete magnetization or a higher field than would otherwise be required. It may also lead to eddy-current losses in the magnetizer itself. Generally, eddy-current losses become more important with larger parts.

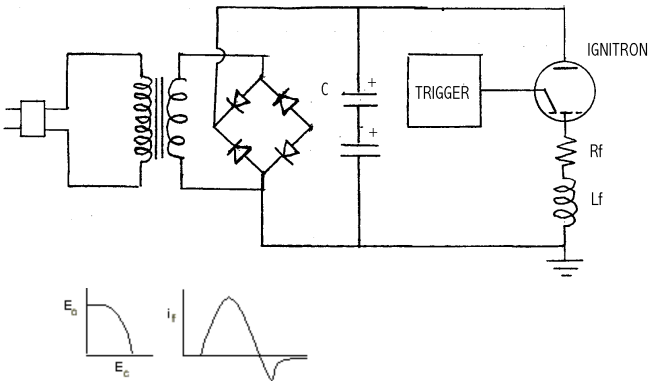


Figure 11. Early Capacitive Discharge Magnetizer (ca. 1944)

7.2.2.4.2. Circuits

In figure 11, the circuit diagram of a capacitive-discharge magnetizer of a simple, early design is shown. The maximum charging voltage of this design cannot exceed that of the capacitors, which depending on when it was made might be from 350 volts to 450 volts. The fixture must be designed so that its resistance is high enough that the magnetizer-fixture combination is overdamped. If this is not done, the system might "ring", that is oscillate the output current back and forth, partially demagnetizing the part. It is very likely, as well, that in spite of the ground connection in the line, current through the cables to the negative terminal of the capacitors will be high enough to cause a significant reverse voltage on the capacitors, which will shorten their life, or even cause them to explode. After the magnetize command is given, the operator may have to wait a little while before starting the next recharge, as the time needed for the ignitron switch to shut off is fairly long, and uncertain. If the operator tries to recharge the capacitors before the ignitron has shut off, the charging current will just be passed through the fixture. The fixture will heat up, and the capacitors will not charge. At this point, the operator must stop, turn off the machine, wait a short time, and try again.

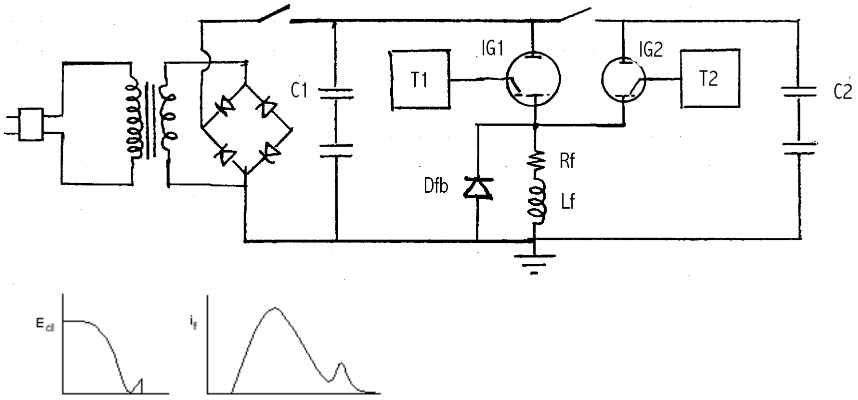


Figure 12. Improve Ignitron Magnetizer with Shutoff Circuit (ca. 1955)

The next circuit, figure 12, shows an improved design. Two banks of electrolytic capacitors are used in series, allowing use of higher voltage. Diode D1 insures that the current through the ignitron cannot flow back into the capacitors. Diode Dfb is very important-it is called the flyback diode, and should be able to carry the peak current of the magnetizer. When the positive terminal of the capacitor banks is near zero, the large inductance of the fixture will not allow the current through it to stop abruptly. Instead, the current recirculates through the flyback diode in a loop, clamping the voltage of the ignitron cathode to zero. The capacitors are protected from negative voltages on the positive terminals, and so the fixture may be underdamped without causing damage. This is important, as underdamped circuits are more efficient in transforming their electrical energy into magnetic energy than are overdamped ones. Switch 2 is closed to charge the second, smaller set of capacitors Cx. It is then opened.. After the main circuit has been turned on and the main capacitor banks are discharged, or nearly discharged, the second ignitron is triggered on. It is typically much smaller than the main switch. The voltage at the cathode of the main switch rises above that of the main capacitor banks. The main ignitron is back biased, and stops conducting. The smaller capacitors Cx are quickly drained, and the second ignitron turns off, too. The main banks may begin recharging as soon as the main ignitron is turned off.

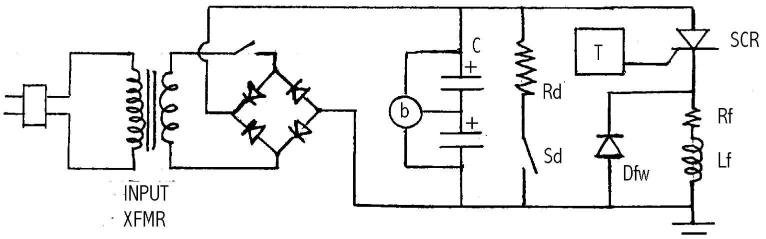


Figure 13. Magnetizer Using SCR (ca. 1965)

A circuit using an SCR is shown in figure 13. The flyback diode is still there, but the SCR shuts of much faster when the current tries to reverse, and a shutoff circuit is usually unnecessary. An additional circuit (labeled “b”) across the capacitor banks is used to balance the voltages across them-that is, to prevent the voltage across one set to become much larger than that across the other. This could be necessary if the actual capacitance value of the two banks is significantly different, which would divide the charging voltage so that the highest voltage would appear across the smallest capacitance, of the two banks in series. In addition, a discharge resistor, Rd, has been added with a switch Sd, normally open. If a dangerous condition is encountered, such as the cabinet door being opened while the magnetizer is charged, or if the power is removed with the capacitors left charged, the capacitors will be discharged.

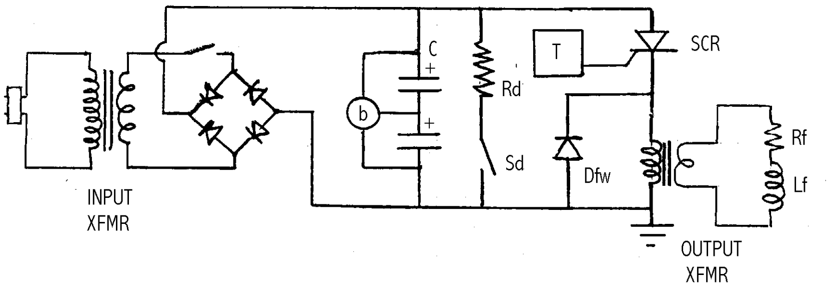


Figure 14. Magnetizer with Output Transformer

In figure 14, the same circuit is shown, but with an output transformer added. The transformer cannot affect the power sent to the fixture (other than to reduce it very slightly due to its own internal losses), but the product of voltage times current in is (nearly) the same as that coming out. By using fewer turns on the output side, higher current at lower voltage is delivered to the fixture. At first, this would not seem to be of any advantage, as one could get the same result by using a larger number of turns, at smaller current, in the fixture to get the same result. There may be advantages to using an output transformer in some applications, however. First, the maximum voltage on the fixture is reduced, which improves safety to the operator. Second, the reduced voltage and fewer turns results in less space in the fixture being needed for electrical insulation, and so the “packing factor” of the conductor in the winding is improved. The transformer adds cost to the system, however, and increases the required power slightly.

An ideal transformer would have no resistance of its own, and no inductance. If such a transformer having a turns ratio of n, that is, there are n turns on the primary side for each turn on the secondary, were to have a charged capacitor C in the primary, while the secondary is connected to a fixture having inductance L and resistance R, and if voltage E appeared across the secondary (the fixture), with current i, then the voltage in the primary circuit is En, the current is i / n, the resistance as “seen” at the primary from R in the secondary is n^2 R, and the inductance in the primary caused by the fixture inductance is n^2L. The damping constant ρ greatly influences the behavior of the circuit. If the value of the damping constant for a series combination of R, L, and C (with no transformer between them) is ρ then the damping constant which results from inserting a transformer of turns ratio n between the capacitance and the fixture (with L and R) is nρ.

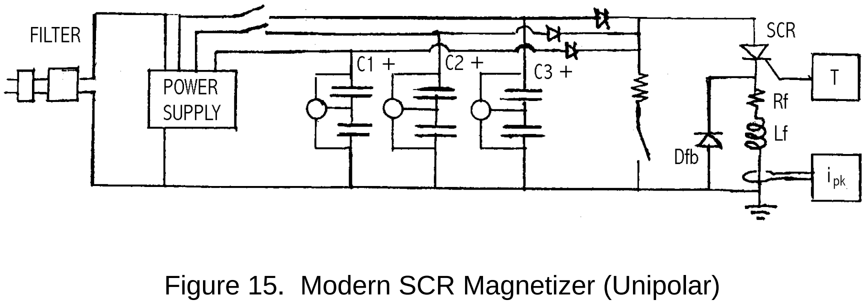


Figure 15. Modern SCR Magnetizer (Unipolar)

The circuit of figure 15 has two significant improvements. The first is that the capacitance may be varied, as well as the charging voltage, and the second is that the peak output current is automatically displayed on the front panel. These are both patented features, however, and are only available on Oersted Technology equipment. The use of variable capacity allows one magnetizer to take the place of many fixed-capacitance machines, so that it may be used with different fixtures of various sizes, for different products. In addition, it permits optimization of the fixture-magnetizer combination. Fixtures are designed for each new application (except for a relatively few cylindrical, straight-through ones), and their cost cannot justify adjustment of the design and reconstruction, unless absolutely necessary. Because of uncertainties, even the best-designed fixture may still fail to meet needs caused by unexpected changes or inaccurate data. A magnetizer with adjustable capacitance may often be used to accommodate these variables. It is often found that production personnel, experimenting with changes of both capacitance and voltage, may improve performance, product throughput, or allow use of different materials.

This magnetizer uses a constant-current charging circuit instead of a large 60 hz transformer. The transformer types typically charge at a high rate at first, but then as the capacitors reach a higher charge the current is reduced by their reversed voltage. As a result transformer-based designs draw significantly more current from the line, for part of the cycle, than does a constant-current device of the same output power.

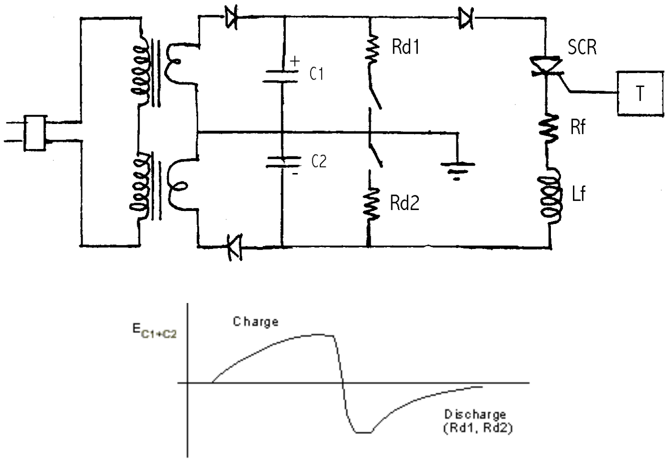


Figure 16. Bipolar Capacitive-Discharge Magnetizer

Figure 16 shows a high-voltage magnetizer with a bipolar design. Two separate charging circuits are needed. Capacitors C1 and C2 are both charged at the same time, with the negative terminal of C1 and the positive terminal of C2 connected together to ground. The combined voltage across the switch SCR is therefore double that on each capacitor. When the switch is triggered, current begins to flow from C1 to C2, discharging both at first, and then recharging them in the opposite direction. No flyback diode is required. As the reverse voltage increases, it gradually reduces and then finally stops the current through the fixture. After the pulse is finished, the capacitors must be discharged through the two resistors R_{D1} and R_{D2} before they can be recharged to start the next cycle.

High-voltage designs are typically much more expensive than medium-voltage ones, for the same energy delivered to the fixture, because of the need for high-voltage capacitors and two charging circuits. As the capacitance value is less, the pulses tend to be short, and at higher current, which necessitates larger diodes and main switch, also increasing the cost. On the other hand, the very low ESR makes them attractive in applications where very short pulses will not excite eddy-currents, in small parts with many poles close together in very-high coercivity material. The circuit shown dissipates less power in the load than does the type using a flyback diode, although the difference is not very significant unless the circuit damping constant is very small (below .15), which is not usually possible.

8. Conditioning / improving Magnet Uniformity

Magnets cannot be produced at present with highly uniform properties, but instead exhibit a range a strengths, etc. The tolerances are relatively wide, from perhaps +/- 7% for the least uniformly produced to +/- 3% for the best, based on total flux from the part at B_r. This range is often too great for specific applications. The magnetic performance of a given magnet cannot be determined until the magnet is magnetized, and that is often first possible after the magnet is assembled and bonded into a finished unit or structure. It may also be the case that the overall performance of a device depends on a combination of factors, none of which can be controlled to sufficient accuracy to meet the performance specifications. The overall performance must then be brought into specification by adjusting the strength of the magnet, based on some measurement which is not directly magnetic in nature (such as force, switching voltage, etc.). For these reasons, it is sometimes necessary to adjust the strength of the magnet by a controlled demagnetization, which is often called conditioning.

The name "conditioning" comes from an earlier time when the only powerful magnet materials available (particularly Alnico) had B-H curves which were convex over the region in which they had to be used. As a result, any (initial) change at all in the direction of lower B led to some demagnetization and a permanent change in the field strength. The only way to prevent this is to deliberately demagnetize the part to the maximum extent expected in operation. The result is a weaker field, but one which repeats during operation, giving a reliable result. More modern materials do not have this problem. Partial, controlled demagnetization of them may nonetheless be needed, as a means of adjustment.

Magnets, are not abruptly magnetized at one level of field, as explained earlier. Instead, some of the domains are more easily aligned than others (if this were not the case, partial demagnetization would not be possible). For best stability of the magnet, it is therefore best to first fully magnetize the magnet, which aligns all of the switchable domains in the desired direction, and then apply a reverse coercivity, reversing the domains which are most easily switched. If instead, the magnet is initially magnetized to only the final field strength desired, the most stable domains are not aligned, while those most easily reversed are left in the "forward" direction, from which the demagnetizing forces are able to disturb them. This is because the interior of a magnet is exposed to demagnetizing flux whenever the magnet is in the second quadrant of operation (positive B, negative H), which is the state in which they are normally used.

To fully reverse the magnetic state of a magnet requires at least as much coercivity as is needed to initially magnetize it, and sometimes more. Controlled partial demagnetization, however, is accomplished at a much lower field, starting at the point in the (Percent B_r versus H_s) curve at which $\%B_r$ first rises above zero. Even full demagnetization (by reversed magnetic pulse) is accomplished at a much lower field than is needed for full magnetization. It should be appreciated, however, that this "demagnetized" state is not the same as the initial, virgin demagnetized state. In the virgin state domains are randomly oriented, without regard to their pinning strength (resistance to change). After demagnetization by reverse pulse, however, the most strongly pinned domains remain in their "forward" direction, while the least strongly pinned domains are reversed, resulting in zero (or near zero) net field.

One may certainly weaken the magnet strength by applying a given, fixed reverse pulse to each of a series of magnets. The variation of strengths within such magnets will be relatively wide, however, and one may expect even more variation than would be found between the same magnets, fully magnetized. To improve the accuracy of the field, it must be measured, an a reverse pulse applied the strength of which depends on the degree of field reduction required. In practice, this is done by repeated measurement and demagnetization, with the strength of the reversed pulse gradually increasing until the required field strength is achieved. There is usually little or no effect if more than one pulse, of the same strength, is applied to the same magnet. If the magnet is demagnetized too strongly, then another magnetization pulse in the forward direction must be made, followed by reversed pulses again. In practice, when one is doing his controlled demagnetization "by hand", one soon learns to roughly predict what adjustment is required, in order to reduce the number of cycles required. When done by automatic means, it may be possible to program an adjustment procedure into the machine to accomplish the same result. A method sometimes used by machine, however, is to simply increase the reverse pulse by some fixed, small increment and test to see if the resultant field is small enough. This clearly takes more machine time. The writer has found that even when doing this adjustment carefully by hand, it may not be possible for a small percentage of the parts to adjust them to the required tolerance, if this tolerance is very small, by operating on the entire part.

If construction permits, however, it may be possible to demagnetize only a small region of the magnet, rather than the entire part, to make the finest adjustment.

It is completely possible to make the decision on the size of the reversed pulse based on some other parameter than magnetic flux or flux density, either by hand or by computer.

Equipment to condition magnets in the manner described, by a completely automatic procedure, may be relatively expensive, unfortunately, as it requires not only a fixture and magnetizing power source, but also means to measure the required parameter to be controlled, and computer (or other) control of the power source. It is also slower, as normally some (usually variable) number of cycles must be accomplished before the part is within specification. For volume production, however, or frequent use at short production runs, it is very cost effective.

9. Measurement of Existing Magnetizers and Fixtures

9.1 Magnetizer Performance

The rated values of standard electrolytic capacitors vary with wide tolerances, a typical specification being –10% to +50%. Even if a magnetizer is manufactured with parts of closer tolerances, replacement parts may vary widely. Manufacturers rarely report the source resistance of their magnetizers. In addition, the magnetizer has some inductance, which results from the construction of the capacitors, from the internal wiring, and possibly from other circuit components (a circuit component used by Oersted Technology to protect the SCR in case of shorting of the output , for example, has a small inductance). The values of the inductance, capacitance, and resistance of the source are needed if new fixtures are to be designed accurately. It is sometimes necessary, then to measure these values directly. A paper by Lee (Ref 3) describes the characterization, that is the determination of these values, of a magnetizer by means of estimating the values, calculating the resulting curve by computer, and then adjusting the values of R, L, and C until a sufficiently good fit to the measured curve is obtained.

As a young engineer many years ago, your writer was directed to use curve fitting to analyze the oscillation of the water level in an atomic reactor. Although the problem was mechanical, not electrical, it was mathematically similar. The results were not very accurate. When we faced the same problem at Oersted, therefore, we looked for a better way, and found one which works very well. Two pieces of special equipment are needed, however. The first is a means of measuring the current with time, for which we built a stand-alone version of the current meters we build into our magnetizers. The second was a load fixture, made not for magnetizing but just for this purpose. It is made of stranded cable, to eliminate the effects of eddy currents in the conductors. The conductor mass must be large, so that the change of resistance due to heating is small. Finally, it is made in a manner to eliminate variation of inductance with frequency, to as complete an extent as possible. The inductance and resistance were also tailored to the values thought to be best for the expected result. The actual values were then carefully measured with a video bridge, over a wide range of frequencies.

A typical plot of voltage across the fixture versus time, and of current versus time, are shown in figure 17. In the voltage plot, at the beginning of the pulse, the slope of the curve is extrapolated back to zero current. At this point, the entire voltage appears across the total inductance, and so:

$$L_T = \frac{E}{\frac{di}{dt}}$$

Where L_T = the total inductance (fixture plus magnetizer).

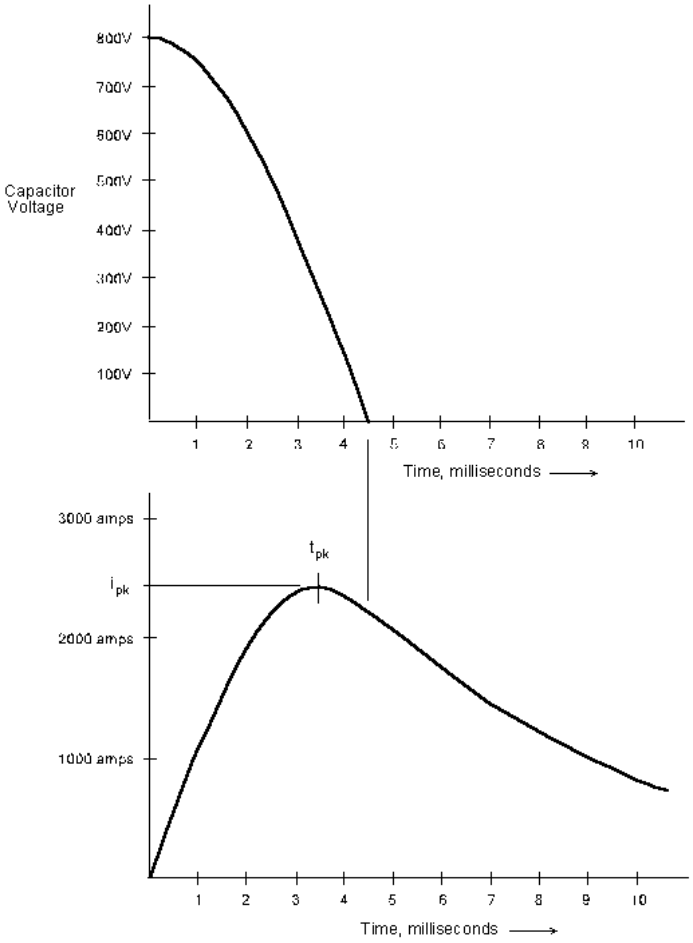


Figure 17. Voltage and Current During a Magnetizing Pulse (Unipolar Type)

At the point where current from the capacitor is cut off (and the capacitor voltage stops dropping),

$$L\frac{di}{dt}+ir=0$$

(where i and di/dt may be found from the current-time curve, and L from the above equation)

$$r=-\frac{L}{i}\frac{di}{dt}$$

The capacitance may be found from the integral of current with time, to the cutoff point,

$$C=\frac{1}{E_0-E_x}\int i\,dt$$

The time at which peak current occurs, and its value, may then be used to check the results. Another means of checking is to calculate the damped frequency,

$$w_d = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

since the time at which the voltage across the capacitors equals zero is:

$$t_x = pw_d$$

This time may be found with better accuracy than that at which peak current occurs.

9.2 Fixture Performance

A fluxmeter is an instrument which integrates voltage with time. Since from Faradays Law:

$$E = n\frac{df}{dt}$$

Then the change of flux across the search coil is:

$$f = \frac{1}{n}\int E\,dt$$

The total flux passing through a magnetizing fixture may be measured by use of a search coil embedded in the fixture, at the inside diameter, connected to a fluxmeter. Because of the large amount of flux involved, these are usually of a single turn only. Before this is done, however, the peak voltage across the search coil should be computed, to insure that it will not exceed the input voltage limit of the fluxmeter. This measure is of the total flux, however, and it divided by the cross-sectional area is an average flux density, not the minimum flux density, which is usually located at the center. If the winding pattern has not been adjusted to produce constant flux density across the cross-section, these two may be considerably different.

Instead, a smaller search coil may be used, possibly wound on a nonconductive rod, to find the flux, and thus by dividing by the search coil area the flux density at that location, averaged over the coil area. For these tests, the fluxmeter must be able to capture and hold a peak value, as the net change of flux over the magnetizing cycle is zero.

Another way to measure the flux density produced in the fixture is by use of a gaussmeter. The instrument must be capable of measuring and holding the result of the fast pulse, however, and the probe used must both have the necessary response and not have electrically conductive reinforcing material (such as an aluminum sheath) which blocks the pulse by induced eddy currents. For use in cylindrical fixtures, an axial probe is needed, whereas to measure radially-directed flux, as in a magnetizing fixture for a multipole ring magnet, a transverse-type probe is required.

Another useful type of magnetic measurement is the stray magnetic field around the fixture, as it is pulsed. This may be needed for safety reasons, or to know how critical it will be to keep the surroundings free of steel objects such as tools.

The ability of the fixture to reject heat is also an important property of a fixture intended for production use. The thermal time constant of the windings is often different from that of the fixture as a whole. These may be measured with embedded thermocouples. The temperature of the winding may also be measured by resistance measurements, if a means to do that is available. The resistance is usually so small that it cannot be measured accurately with ordinary instruments such as volt-ohmmeters. There are instruments sensitive enough to measure them, however. Another way is to pass a known current from a power supply through he winding, and then measure the resulting voltage. Many volt-ohmmeters are capable of doing this to good accuracy. Usually the power supply meter is not a sufficiently accurate measure of the current, and it must also be measured separately. The current used must not be high enough to affect the reading by heating the fixture, of course.

As the fixture inductance and resistance may be a function of frequency, it is best to measure them over the expected range of operation, not just at one frequency. At Oersted, we do this with a video bridge.

As the fixture is intended for high-voltage use, it is important to check the electrical resistance to ground. This must be one with a "High-pot" or "megger" instrument capable of generating test voltages as high or higher than that at which the fixture will be operated. The reason for this is that the resistance at high voltage is often nonlinear- a fixture which passes the resistance test at even 500 volts may fail at 1000 V.

10. Safety Considerations and Features

10.1. General

Safety is certainly a consideration in using magnetizers and their fixtures, as the voltage and current levels are high enough to be lethal. The writer has researched the question and asked many others with considerable experience in magnetizing, however, and has never discovered a single case where someone has been killed, in the entire history of use of this class of equipment. He has encountered a few cases of persons being badly shocked (producing temporary injury), but only if the person ignored all reasonable safety precautions (such a deliberately removing all safety controls, taking panels off, charging up the capacitors, and reaching into the machine to touch a bus bar, in order to check its temperature!). The potential for a fatal accident certainly exists, however, and must not be ignored.

A major source of concern is bare contacts between the magnetizer cables and fixtures. This is often seen, but is a great and unnecessary hazard. A magnetizer should never be used if the cables are damaged, as the high voltage could short out to the surroundings. It may be helpful to use an electrically insulating mat on the floor in front of the magnetizing station. Some rubber mats are not electrically insulating, because of filler material used in the rubber. A type of mat, however, called Switchboard Grade, is made for this service, and can withstand very high voltages and considerable wear.

. If the fixture is used on a metal table, it may be attracted or repelled from it with considerable force. If a fixture must be used on such a table, therefore, it should be mounted above it using nonmagnetic and non-electrically conductive spacers (usually only a short distance is sufficient, such as 6 in.) and then securely fastened down to it. Metal objects, such as sheet metal plates, should not be laid across the top of the fixture in operation.

Parts inside a magnetizing fixture may be thrown out during the pulse. Magnetically permeable parts located below center may be accelerated upward, towards the center, but arriving here after he pulse has stopped. The part then continues upward, out of the fixture. Parts which are above center, which are electrically conductive, may experience large eddy currents due to the rapid change of field. These eddy currents are in the direction to produce a magnetic field which opposes the field which caused them, and so the parts are repelled from the fixture.

10.2 Safety Considerations in Equipment Design and Installation

It is certainly a good idea to provide some means to hold a part in place during magnetization, if the fields are high enough to cause the parts to "jump",even though this should not be done by use of an unprotected hand. This can be done by use of part holders, made to accept the part, held in place by screws with nonconductive handles, lever clamps, etc., or a locking cover or guard. A good material for such a guard or cover is polycarbonate plastic, one trade name of which is "Lexan", as this material is unusually tough. It is often used as bullet-proof "glass", for example.

Some magnetizers are equipped with resistor banks which allow energy stored in their capacitor banks to be discharged within the magnetizer when an unsafe condition is detected. For example, the capacitors may be discharged if the cabinet door is opened, or if the machine is shut off or the power fails. Another safety feature is to supply a means within the magnetizer which prevents charging or discharging if a normally-closed, "failsafe" circuit is opened. Such a circuit may be combined with capacitor discharge circuit. It is helpful to have a thermal sensor on the fixture and safety circuit such that if the fixture overheats, due for example to failure of the coolant, that operation is prevented until the problem is corrected.

The magnetizer cabinet should be effectively grounded, using a heavy-duty connection which will not be burned off if a circuit short directs the pulse into it.

No one should attempt to service a magnetizer who is not trained in high-voltage work.

10.3 Cleanliness

Cleanliness around the magnetizer is important. It seems almost unreasonable to point it out, but cups of coffee or other liquids should not be placed on top of magnetizers or fixtures! Flammable liquids such as solvents, or electrically conductive liquids such as water, drinks, etc. should not be allowed in the vicinity of the magnetizer, fixture, or cables, or obvious reasons. Loose metal parts, tools, fasteners, etc. may be thrown violently by action of the magnetizer, and should not be closer than several feet from the equipment. Loose metal parts, such as nuts and bolts, may be thrown out of the fixture at high speed if accidentally left inside or underneath

10.4 Fire Protection

Fire protection of the area in which magnetizing equipment is to be used should be appropriate for high-voltage, high-power electrical machinery. An automatic water sprinkler, turning on over or near the equipment due to smoke or fire from some source, possibly another machine nearby for example, could be very dangerous. Carbon-dioxide (CO_2) extinguishers are spectacular in operation but not very effective. Type "C" dry-powder type fire extinguishers are nonconductive and effective at fighting a fire, but the fine powder is extremely difficult to clean. The result of using an extinguisher of this type nearby may well be the destruction of expensive electronics. Halon extinguishers work, but the material is no longer in production, and so future refills may be problematical. There are replacement materials, one called "Halotron" (Amarex Corp.) and a second called "Cleanguard" (also known as FE36) (Du Pont Co.) which may be suitable.

10.5 Effects of Stray Fields

Persons with medical implants, especially pacemakers, should not be within about five feet of a magnetizer (a reasonable limit is a maximum leakage field of five gauss) or fixture during operation.

Occasionally an operator will want to hold a part within a fixture while magnetizing it. This should never be allowed. If the operator has a ring, it might conduct high eddy currents, generating heat and causing large mechanical forces. Exactly what the magnetizing pulse, at many thousands of gauss, might do to the person directly is unknown, but the blood would probably conduct large electrical currents with possibly dangerous results. Although it is unwise, however, this writer has often seen it done, repeatedly, with no apparent bad effect. Far lesser fields, from operating the magnetizer, do not seem to have any effect, and numerous operators have used such equipment for many years, enduring millions of pulses, without harmful effects of any kind.

11. Demagnetizing

If a magnet is gradually heated to a higher and higher temperature, the magnetic properties may be affected, which return to their former state when the magnet is cooled. These are referred-to as reversible properties. When the magnet is heated above some point, however, usually called the Curie temperature (a few prefer to call it by another name), all magnetism is abruptly lost, over a very small range of temperature change. If the magnet is then cooled down, no residual magnetism is observed, and the magnet behaves as it did in the virgin state. This method cannot be used, of course, if the magnet is bonded, and the bonding agents melt or char at a temperature below that of the Curie temperature. The state so produced is different from that caused by demagnetization from a single reversed pulse, and also different from that caused by repeated reversal of magnetization (although perhaps not as much different, in the latter case).

Another method of demagnetization is to reverse magnetize the part with a relatively high field, then again reverse the field at a lower level, and continue until the field is zero, or low enough to have no further effect. Although this method seems at first to be ideal, it does have some limitations. A few materials magnetize best from the virgin state, and require an extremely high field to fully reverse magnetize afterward, possibly an unobtainably high field. The first reverse pulse may actually be made at a lower field than that needed to magnetize, but the result is to leave the most strongly-pinned domains in one direction. If the field is then reduced by too large a margin, demagnetization becomes uneven. On the other hand, if the reversals are closer together, many cycles are needed, and the part may heat up from both hysteresis and eddy-currents. The method is often successful, however. One means to do this is to design a circuit, including the capacitors, fixture inductance, and resistance so that it "rings" or oscillates after triggering, with some energy absorbed during each cycle by both the capacitor ESR and the winding resistance. Another method, often used with low-coercivity materials such as steel, is to use a coil which is powered directly from a power line at line frequency, and then withdraw the part to be demagnetized from the field, so that each element experiences a gradually diminishing field strength as the distance from the coil increases. This cannot be one with materials requiring a very high coercivity, of course, and even then heating is a major limitation.

12. List of References

In the past, relatively little has been written about magnetizing. The references given here are sometimes for particular subjects which affect magnetizing, but may not be primarily written with that subject in mind.

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