DESCRIPTION OF BASIC TYPES OF PERMANENT MAGNET APPLICATIONS

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From manufacturer's literature and previously presented workshop discussions we find a great variety of magnet materials available to the user. There is no single general purpose magnet. To obtain an optimum as well as economical design for a specific device and satisfactory performance, one must carefully select the proper magnet material. Permanent magnet design not only involves the determination of the magnet's physical shape and tolerances, but also determination of the magnet's associated magnetic circuit or hardware (See Figure 1). Many times a properly designed more expensive magnet yields a more economical solution to the design objective. Hence, any economical evaluation should be made on the merits of the total magnetic circuit required and not just on the magnet itself.

The design job is a highly specialized one. Magnet material selection is a matter of careful judgment plus knowledge of the material properties and how they behave in the magnet circuit under consideration. A successful PM design usually results when close cooperation is exercised between the magnet manufacturer and user.

Besides required magnetic performance, the designer must also consider temperature requirements, external demagnetizing influences, weight, cost, space limitations and whether the device is for static or dynamic operation. However, the basic principles relating to permanent magnet application apply to all PM materials. Some of these applications principles will now be discussed.

The permanent magnet magnetic circuit consists of two basic parts: the magnet itself and the air gap to which the flux or flux density is to be supplied as shown in Figure 2. The magnet and air gap are most often augmented by soft iron poles, referred to as flux concentrators, directors or return paths. A second magnetic field produced by another magnet or an electromagnetic field may also be present.

The first vertical sequence of Figure 2 represents a magnet and its associated air gap as represented by dashed flux lines. For illustration purposes, the average point at which the magnet operates is shown by the intersection of the magnet's demagnetization curve and the circuit permeance coefficient.

The second sequence of Figure 2 incorporates the same magnet along with soft iron pole pieces. The soft iron pole pieces collect the flux and direct it to the air gap. The flux concentration, provided by the pole shoes, serves in three ways:

a. The magnet's useful flux is directed to the desired location.

b. The flux density in the air gap is increased.

c. The circuit permeance coefficient is increased thereby moving the intersection with the demagnetization curve closer to the residual flux density of the material and increasing the flux-giving capability of the magnet.

Rarely is a magnet used without some form of soft iron in the magnetic circuit.

The third sequence of Figure 2 represents the effect of an externally applied field in opposition to that of the magnet. As the external field is increased, the permeance coefficient line P shifts to the left as represented by the dashed lines. The effect of the external field acting on the magnet is to change the operating point of the magnet.

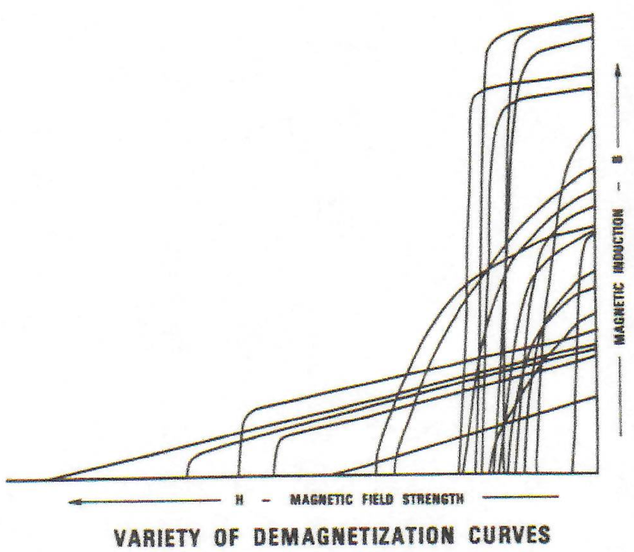
When a specific design problem involves only a magnet, iron poles and an air gap, the problem may be referred to as the static case shown in Figure 3. In this event, the normal demagnetization curve is used to determine the magnet dimensions. Minimum magnet volume required to do the job results when the magnet is so dimensioned that its operating point on the normal demagnetization curve corresponds to the material's maximum normal energy product.

When the design problem previously discussed also involves a strong opposing external field acting on the magnet, one normally uses the material's intrinsic demagnetization curve for solution of the problem. This is referred to as the dynamic case. The external field can be that of a second opposing magnet in the system or another magnetic field produced by an electromagnet. Minimum magnet volume results when the magnet is so dimensioned that its operating point on the intrinsic demagnetization curve, at the time the external opposing field is at its maximum value, corresponds to the material's peak intrinsic energy product.

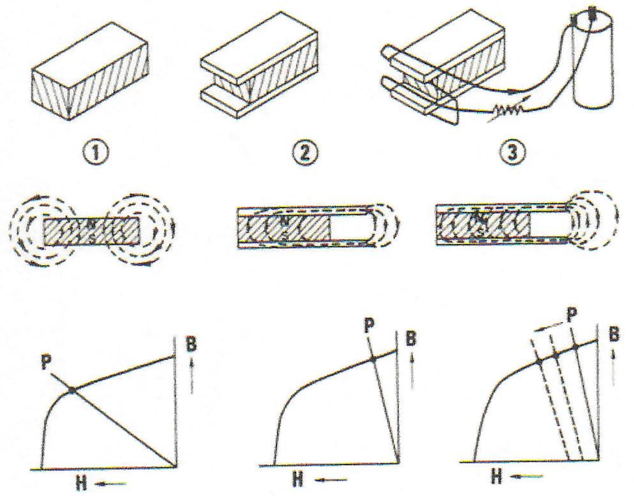
Hence, when external demagnetizing fields are not present on the magnet (static case), the peak normal energy product is considered to be the material's figure of merit, whereas if external demagnetizing fields are present (dynamic case), the peak intrinsic energy product is considered to be the material's proper figure of merit.

It should be understood that magnets cannot be designed by inserting numbers into a few formulae and expecting the length, cross-section and shape of the magnet to emerge. The working conditions of a magnet are incredibly complex, and design formulae are only simplified approximations. At best, they give a general indication of the kind of size and shape required.

Figure 4 attempts to indicate some of the difficulties encountered. The permeance coefficient, P, is illustrated here as the product of the magnet length, l_m, and air gap area, A_g, divided by the product of the magnet pole area, A_m, and air gap length, l_g. Due to fringing (or spreading out) of the flux at the air gaps shown by the dashed lines, the air gap and air gap length are not well defined and must be approximated by the effective area and effective length to determine the magnet's operating point, B_1.



VARIETY OF DEMAGNETIZATION CURVES
FIGURE 1



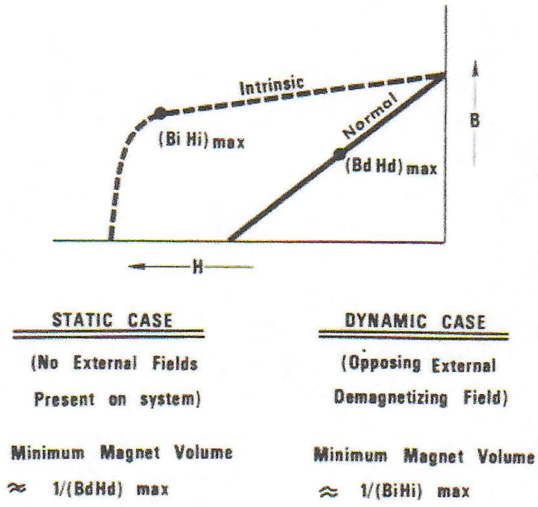
PM MAGNETIC CIRCUITS
FIGURE 2

Placement of the magnet in the magnetic circuit is also very critical. Due to leakage flux paths in the magnet circuit, indicated by the dashed line arrows between magnet poles, all of the magnet's flux does not reach the air gap. This lost flux, called leakage flux, reduces the magnetic circuit efficiency. The magnetic circuit efficiency is an indication of how much of the magnet's flux actually reaches the air gap. In general, the closer the magnet is placed to the air gap, the higher will be the magnetic circuit efficiency. Magnetic circuit efficiencies can range from 25% to 95% efficient.

Since magnets can be magnetized, it stands to reason they can also become demagnetized. There are three basic demagnetization fundamentals.

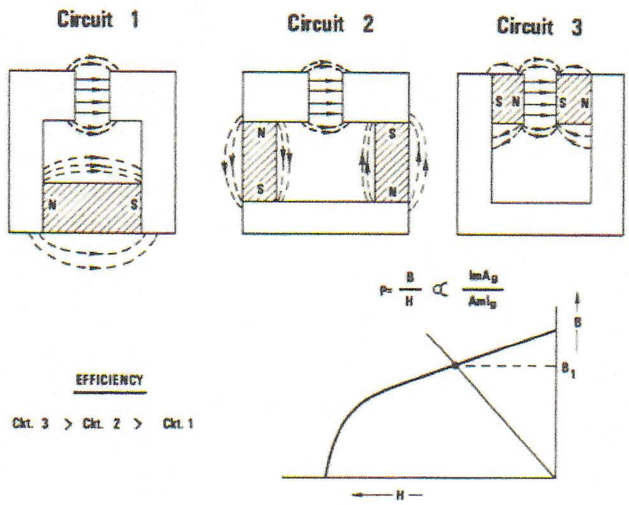
The first, shown in Figure 5, is self demagnetization, sometimes referred to as open circuit or removal. Case 1 represents a magnet with soft iron pole shoes. The unit permeance coefficient of the circuit results in the magnet operating at point "A" on the demagnetization curve. If the soft iron pole shoes are removed, the magnet's effective air gap length is increased. The permeance coefficient is reduced and will intersect the demagnetization curve at some point "B". If point "B" is below the knee of the demagnetization curve the magnet is said to have been partially demagnetized. To prevent magnets from self demagnetizing it is normal practice to magnetize the magnet after assembly in its associated magnetic circuit.

A second cause for demagnetization to occur is subjecting the magnetic circuit to low temperature (See Figure 6). The thin line is the magnet material's demagnetization curve at normal operating temperature. Most magnet materials have temperature coefficients of coercive force and/or residual flux density. Hence, the shape of the material's demagnetization curve changes as magnet temperature changes. The heavy line represents the magnet's demagnetization curve at some low temperature. If the magnet is subjected to this low temperature we see that the load line intersects the demagnetization curve at point "B". Partial demagnetization will have occurred if point "B" is below the knee of the demagnetization curve as represented.



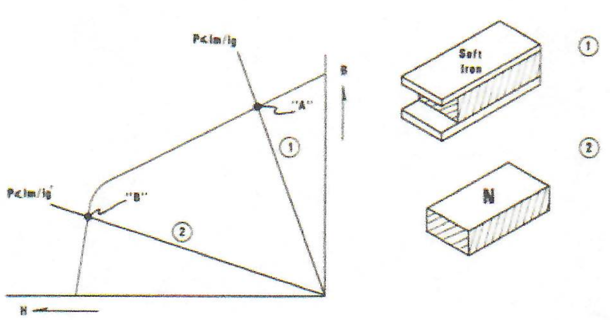
DESIGN FOR MINIMUM MAGNET VOLUME

FIGURE 3



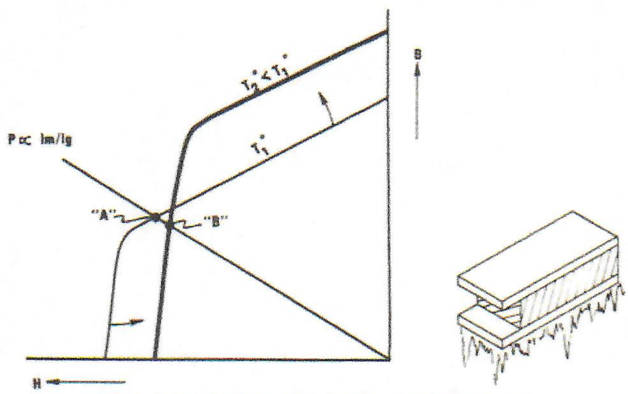
FRINGING AND LEAKAGE PATHS

FIGURE 4



SELF DEMAGNETIZATION (REMOVAL)

FIGURE 5



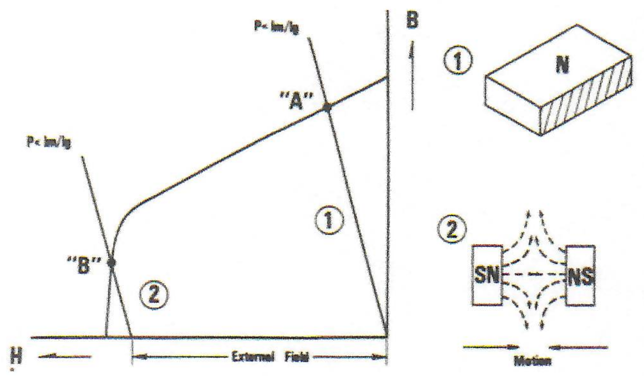
LOW TEMPERATURE DEMAGNETIZATION

FIGURE 6

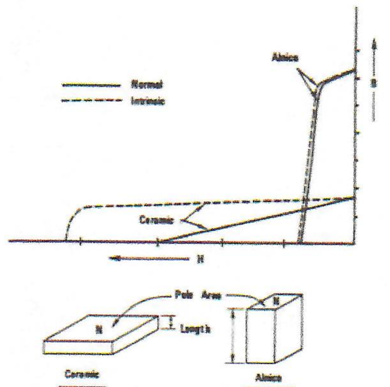
The third type of demagnetization, shown in Figure 7, is that due to an opposing external field acting on the magnet. For illustration, the external field is represented by two magnets opposing each other. Either magnet by itself would operate at point "A". As the magnets are brought together, each magnet tends to drive the other magnet down the demagnetization curve. The effect of an opposing external field acting on a magnet is to move the load line to the left and parallel to itself as indicated by the two load lines. If the external field becomes large enough to drive the magnet beyond the knee of the demagnetization curve, partial demagnetization will have taken place. In application, the external field can be either permanent magnet or electromagnet oriented.

For proper application of the magnet, one must design the magnet dimensions such that none of the three demagnetization effects will occur during the life of the product, thereby changing its operation.

There are two major commercially available permanent magnet categories whose demagnetization curves are shown in Figure 8. These are the Alnicos and Ceramics. Ceramic magnets are typified by their high coercive force and relatively low residual induction compared to the Alnicos having higher residual induction but lower coercive force.



EXTERNAL FIELD DEMAGNETIZATION
FIGURE 7



TYPICAL CERAMIC AND ALNICO MAGNET DEMAGNETIZATION CURVES
FIGURE 8

In terms of magnet geometry, high coercive force permits designers to use shorter magnet lengths (distance between poles), whereas high induction permits smaller magnet cross-sections (pole areas). High coercive force also offers greater resistance to external demagnetizing fields.

Since the magnet dimensions may often be juggled to meet the physical design requirements, one should not arbitrarily eliminate the Alnico or Ceramic magnet class without determining the economics and other merits of one class over the other.

Ceramic magnets have an electrical resistivity between 10^3 and 10^{10} ohm-centimeter, whereas Alnico magnets are conductors. Therefore, Ceramic magnets are used in applications where metal magnets would cause short circuits or high eddy current losses in the presence of alternating current fields.

Ceramic magnets are lighter in weight than the Alnicos. The specific gravity of the Alnicos is about 7 compared with 4.5 to 5 for Ceramics.

The temperature coefficient of residual flux density for the Ceramic magnet of about 0.19%/C° is about ten times that of the Alnicos, but only one-half that of the temperature coefficient of resistivity for copper. Hence, the change in field strength with temperature for the permanent magnets is less than that encountered when using electromagnetic wound fields.

Several of the more general classes of applications will now be discussed. An understanding of the aforementioned demagnetization fundamentals and design principles will be helpful.

First to be considered will be the power conversion devices whose function is to convert energy from electrical-to-mechanical or mechanical-to-electrical. Examples include motors, generators, alternators, magnetos, loudspeakers and relays.

MOTORS, GENERATORS AND ALTERNATORS

The magnet is used to supply flux for one of two magnetic fields required to achieve the conversion. In the case of the motor, the output is rotation or mechanical work. For the generator or alternator the output is electrical power; DC for the generator and AC for the alternator.

Advantages of permanent magnet excited machinery over their electromagnetically excited counterparts are:

c. Cooler running

d. Greater power density

e. Smaller size

f. Less weight

g. Better regulation-feedback excluded

h. Increased reliability

i. Cost savings

Most of these advantages are a direct result of the elimination of the wire wound field.

Required hardware, operating principles and magnet behavior are all somewhat similar for the motor, generator or alternator. For this reason, the permanent magnet field DC motor, which will be considered in depth, should suffice for giving the background and understanding of the magnet's function and behavior in these applications. The generator and alternator will be considered in more general terms.

The permanent magnet DC motor consists of three basic parts:

a. A laminated iron core armature wound with a series of copper or aluminum coils connected to a commutator.

b. A pair of Ceramic or Alnico permanent magnets.

c. An outer iron or steel shell.

A sectional view of the Ceramic PM motor is shown in Figure 9.

The steel shell, used as part of the magnetic circuit, serves as part of the magnet's flux return path. The steel shell wall cross-section between magnet segments should contain sufficient area so as not to saturate due to the flux produced by the magnets. Steel shell flux densities in the order of 15,000 to 17,000 gauss are commonly used.

The function of the magnet field pieces is to supply one of the two magnetic fields required to produce motor action.

The air gap length, l_g, provides the mechanical clearance necessary between the rotating parts. Typical air gaps range between 0.02 and 0.10 centimeters depending upon magnet material used and size of the motor.

The armature iron lamination stack provides the inner portion of the magnetic flux path as well as housing the copper coils which are wound in the lamination slots. DC power applied to the copper coils supplies the second magnetic field required to produce motor action.

A commutator and brushes are used to apply the DC power to the armature coils. The commutator serves as a switch, as the armature rotates, so as to always keep the magnetic field produced by the armature in the proper direction.

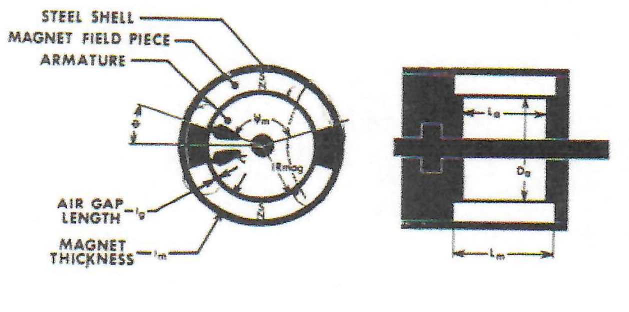
Figure 10 illustrates a variety of Ceramic and Alnico magnet field configurations. The Ceramic magnets are almost always used in conjunction with soft iron steel rings and are magnetized through the radial dimension. The steel portions of the Alnico assemblies are as indicated by the cross-hatched areas. Typical flux paths are indicated by the dashed closed loops. In general, the pole face areas of the Alnico field configurations are smaller than those of the Ceramic magnets, whereas the magnet lengths of the Alnicos are greater than those of the Ceramics. The reason for this is due to the difference in shape of the material's demagnetization curves.

The determination of useful magnet flux for the Ceramic magnet (see Figure 11) will now be illustrated. The magnet pole area for a particular set of Ceramic magnet segments is proportional to the magnet pole arc, psi_m, times the magnet axial length L_m. On the normal demagnetization curve one constructs the "unit permeance" or operating line slope shown simply as l_m/l_g. The intersection of the two curves indicates the flux density, B_m, at which the magnet is working. The total magnet useful flux, Φm, coupling the armature windings is equal to the area, A_m, of the magnet pole, times the working flux density, B_m.

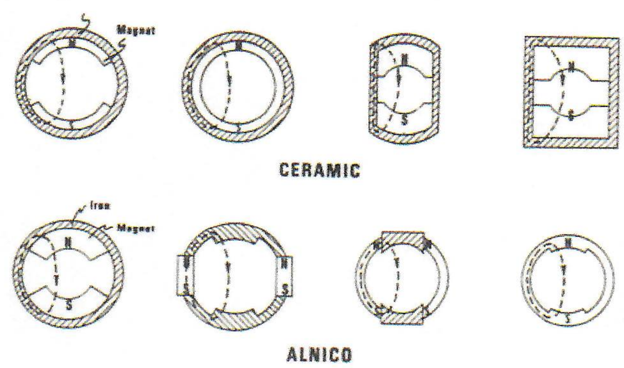
The relationship of the magnet flux, Φm, to motor performance is as illustrated by the speed and torque equations shown on Figure 12. It should be noted that the motor speed is inversely proportional to the magnet flux, whereas the torque is directly proportional to the flux. By proper juggling of the voltage, magnet flux, armature turns and armature resistance, one can determine the magnet pole area, the armature stack length and armature winding necessary to obtain the desired speed-torque curve. It should be noted that the speed-torque characteristic of a PM field motor is essentially a straight line.

The PM motor is a DC motor and will, therefore, only run on DC or average power. This could be regulated DC, battery, or rectified full wave of half wave power.

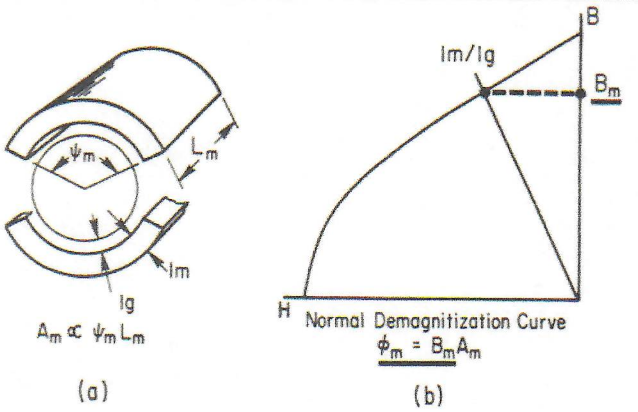
A major concern in PM motor design is to insure that the magnet will remain magnetized for all conditions to which the motor is subjected. Demagnetization protection must be designed for low temperature and the influence of external fields as produced by the armature mmf.



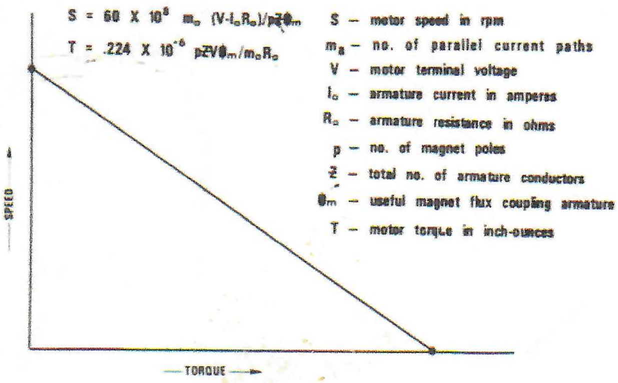
CERAMIC PERMANENT MAGNET MOTOR PARTS
FIGURE 9



MOTOR FIELD ASSEMBLIES
FIGURE 10



MAGNET FLUX DETERMINATION - CERAMIC
FIGURE 11



PM MOTOR CHARACTERISTICS
FIGURE 12

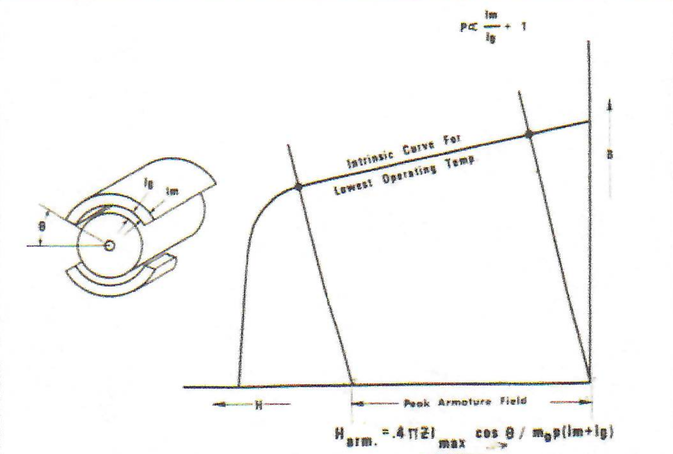
The demagnetization curve shown in Figure 13 is the intrinsic demagnetization curve corresponding to the lowest temperature at which the motor is ever expected to operate. The permeance coefficient line, determined by the ratio of the magnet length, l_m, to the air gap length, l_g, pinpoints the magnet's operating point when armature current is zero. As the current to the armature increases under motor load, the load line shifts to the left. When the motor draws maximum current, generally at stall, the load line should have shifted all the way to the knee of the demagnetization curve. With these conditions present, the motor is considered to possess adequate demagnetization protection using the minimum magnet volume possible.

From the equation, H_{ARM} (Figure 13), it becomes apparent why the magnet length, l_m, is greater when using Alnico magnets than Ceramic magnets since H_{ARM} must be limited to smaller values due to the associated lower intrinsic coercive force values of the Alnicos. However, the magnet pole area, to achieve a given magnet flux value, can be smaller for the Alnico magnets due to their higher values of residual flux density. Magnet volume for a given motor performance is generally comparable for an Alnico and Ceramic magnet design.

EMF $E = \phi ZNP/60a$ V

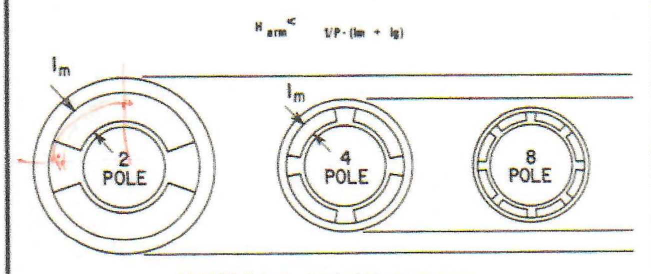
Permanent magnet field DC motors find wide appeal in the automotive, home appliance and power tool industries as well as in a great variety of general purpose type applications.

The usefulness and advantages of the multipole motor will now be touched upon. Traction motors or starter motors having high torque outputs and exhibiting extremely high armature reaction are generally of the multipole construction. The reason for this is, that when we go from 2-poles to 4-poles (see Figure 14), the peak armature field associated with the 2-pole motor is reduced by a factor of two for the 4-pole motor. From the equation, H_{ARM} (Figure 13), it can be seen that the required magnet length is cut in half. The same motor speed-torque characteristic and armature size are maintained. Thus, a general rule of thumb is, that every time the number of poles is doubled, the required magnet length, l_m, and steel shell wall thickness is reduced in half. This means that required magnet volume and steel shell volume is cut in half.



PM MOTOR DEMAGNETIZATION DESIGN CONSIDERATIONS

FIGURE 13



MULTI-POLE CONFIGURATIONS

FIGURE 14

In the case of a generator, the design techniques and behavior of the magnet are very similar to those of the PM field motor just discussed. If a PM motor is driven mechanically, DC power can be extracted from the motor terminals. The volt-ampere characteristic of a PM generator as shown in Figure 15 is a straight line similar to that of the speed-torque curve of a PM motor. The terminal voltage emf is given by $Vg = (p\Phi_m ZS/m_a 60 \times 10^8) - IR_a$. The regulation of the generator is determined by the IR_a voltage drop of the armature resistance.

Proper design, to prevent demagnetization, should be carried out for low temperature and peak current conditions which would occur at short circuit.

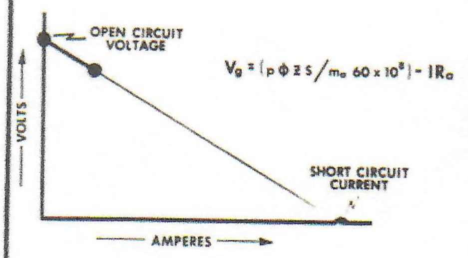
Alternators are used to generate AC power. A typical Ceramic magnet and Alnico magnet assembly are shown in Figure 16. Note the typical magnet geometry of short length and large pole area for the Ceramic magnet alternator as compared to the long length small pole area for the Alnico assembly. Typical flux paths through magnets, steel shell or pole shoes, and stator are as shown by the dashed line closed loops. As the magnet field assembly is mechanically rotated around the copper wound stator, the flux direction reverses through each of the copper coils, thus creating generated AC power.

A great asset to the PM field generator or alternator is that when the magnet field assembly is used as the driven member, the copper wound stator requires no slip rings or brushes. This is not so in the case of the electrically excited generator or alternator. Thus, PM rotating field designs avoid the potential fire hazards and service requirements of alternators utilizing brushes. Brush sparks are one of the primary sources of internal fires.

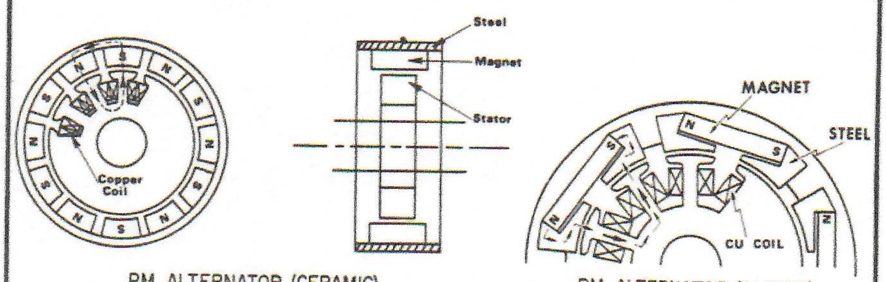
Permanent magnet engine powered portable alternators ranging in output from 100 to 5000 watts are currently being used for recreational and emergency standby use.

This fact, the elimination of slip rings, lends itself well to the application of permanent magnets in the flywheel magneto. The magnet field portion of the magneto shown in Figure 17 is simply one section of an alternator. The magnet flux through the center E-core frame leg reverses as the E-core frame passes the magnet assembly. A voltage proportional to the rate of flux change is generated in the copper coil wound on the center leg of the E-core. This generated voltage is transformed to a very high level and is ultimately used to fire a spark plug once for each revolution of the flywheel.

For each of the aforementioned applications it is interesting to note that the ability of the magnet to service its intended purpose has improved with improvements in the material's peak intrinsic energy product which is a measure of a permanent magnet's ability to induce a field in a magnetic circuit including itself, air gap and return magnetic path in conjunction with resisting demagnetizing forces exerted by the system on the magnet.

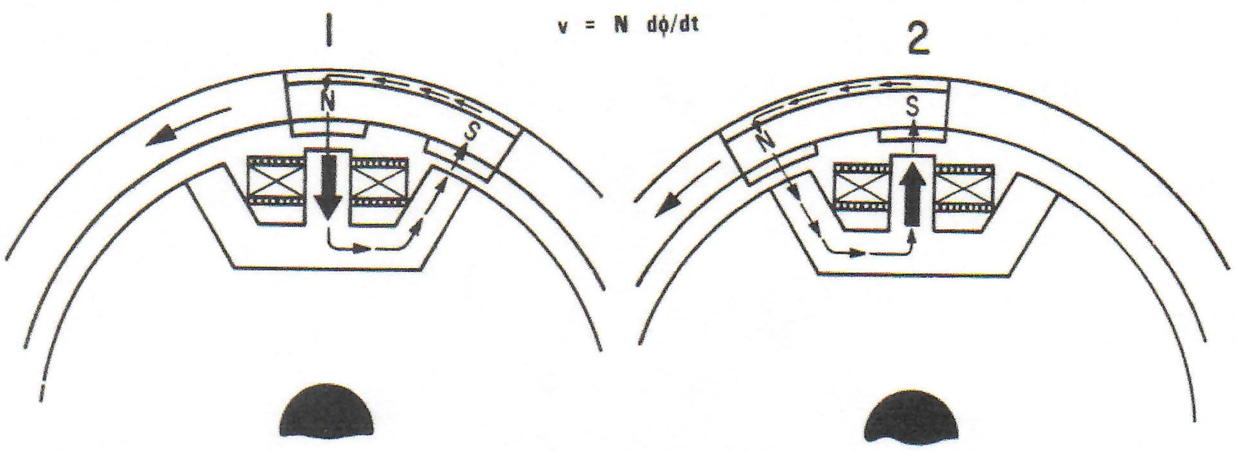


GENERATOR CHARACTERISTICS
FIGURE 15



PM ALTERNATOR (CERAMIC)
PM ALTERNATOR (ALNICO)

PM ALTERNATORS
FIGURE 16



FLYWHEEL MAGNETO (CERAMIC)
FIGURE 17

ELECTRO-ACOUSTIC DEVICES

Most electro-acoustic devices produced today employ permanent magnets in an electro-dynamic, moving armature or variable reluctance transducer system. These include telephone receivers, microphones, disc recorders, headphones and loudspeakers.

The loudspeaker has been selected as one example to exhibit this class of applications. Several magnetic circuit arrangements used in loudspeaker design are shown in Figure 18. The first is an Alnico design using a centerpole magnet. Magnetic circuit efficiencies, or percentage of magnet flux directed across the air gap, range between 40% and 65%. Gap flux densities on the order of 5000 to 10,000 gauss are achieved.

The second structure of Figure 18, also incorporating an Alnico magnet, but of toroidal shape, has a magnetic circuit efficiency of only about 35% due to high external leakage paths associated with the Alnico magnet. However, air gap flux densities on the order of 10,000 to 14,000 gauss are commonly achieved.

The third structure shown in Figure 18, an oriented Ceramic magnet structure, uses a flat disk-shaped magnet. Magnetic circuit efficiencies in the range of 30% to 70% are achievable with air gap flux densities ranging from 10,000 to 15,000 gauss.

For any given magnet geometry, the magnetic circuit efficiency decreases as the air gap flux density is increased. Also, the closer the magnet is placed to the gap, the higher is the magnetic circuit efficiency.