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Towards manufacturing of perfect magnets

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ABSTRACT

The paper describes a magnetizing machine for producing permanent magnets of desired magnetization pattern by use of feedback control. This will in theory mean that an ideal magnetization pattern can be realized, what could be described as a perfect magnet. The machine is to be used for applications requiring high accuracy magnets in terms of the shape of the magnetized area. This is, for example, important for reducing cogging in electrical motors. Results of initial experiments involving use of the machine are presented. The functionality of the machine from a production standpoint and modifications of it that could be useful for mass production purposes, the properties of materials used for magnets, processes involved in manufacturing workpieces that are to be magnetized are discussed. Applications that can benefit from use of a machine of this type are compared with more traditional solutions.

1. INTRODUCTION

A perfect magnet, i.e. one in which the magnetic field of each point on it can be determined and be created accordingly during its manufacture, does not currently exist outside the laboratory. Many of the today's applications could benefit considerably if such magnets, producible in any desired pattern, were available. The present article is concerned with a newly developed machine, referred to as *the magnetizer*, having the ability to produce, by means of feedback control, magnets of high accuracy having whatever basic pattern of the magnetic fields in one particular dimension is desired. Although the magnetizer is unable to affect the magnetization of individual atoms, from a macro-perspective a magnet produced by it can be provided with the properties desired. The idea of constructing such a machine stemmed from work concerned with attempting to produce the characteristics desired in PM (permanently magnetized)-excited electrical machines. Although the primary goal for the magnetizer is to solve problems of this sort, it can be conceived as being able to solve problems of other sorts as well. [1-3]

1.1. ELECTRICAL MACHINES

Electric motors have become one of the commonest components in modern electronic equipment. They can be found, differing widely in type and size, in everything from toys to cell phones, computers and cars. Common to all these motors is that the rotation in them is created by magnetic forces*, usually stemming from permanent magnets in combination with electromagnetic fields created by the current in the windings, so-called PM motors.

PM motors generally have a stator containing copper windings embedded in laminated iron and a rotor in which the magnets are glued in the desired pattern of north and south poles. For some motors of this type, however, such as many computer-fan motors, the magnetic element is manufactured as a single magnetic unit having several magnetic poles, which saves assembly costs. So-called multi-pole magnets are usually molded devices composed of magnet powder and plastic composite, magnetized by use of simple methods for creating square-waved patterns. A problem of motor magnets using this magnetic pattern is that of large magnetic transients induced during rotation creating high-frequency harmonics, which results in power losses, electromagnetic disturbances and vibrations, and thus noise as well. A very large starting current is also needed to overcome the static forces, called the cogging effect, created by the permanent magnets in the rotor together with the iron in the stator. Problems connected with cogging are particularly noticeable in a number of different single-phase, multi-pole machine constructions, since knowledge of and control over the magnetization pattern present in a magnetizing are important constraints during the design of

* Motors driven by electric forces exist but are not yet used in real applications.

such a machine. [2, 3] If instead the magnetization has the shape of a sine wave, for example, such problems can be solved. [1, 2] Figure 1 shows the design of a motor for a typical computer fan, one making use of a multi-pole magnet. The graph in Figure 2 shows the magnetic field pattern of the magnet.

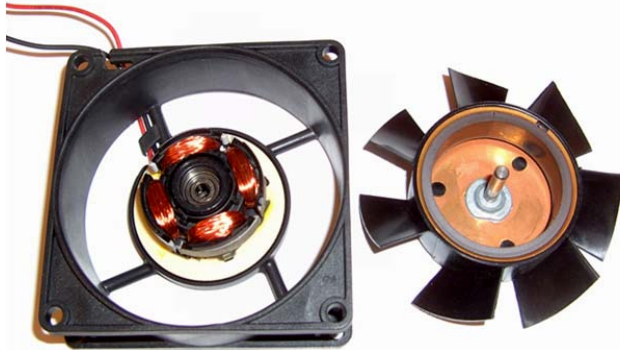


Figure 1: A 4-pole DC-motor in which a multi-pole magnet is placed on the treated iron surface at the back of the fan rotor.

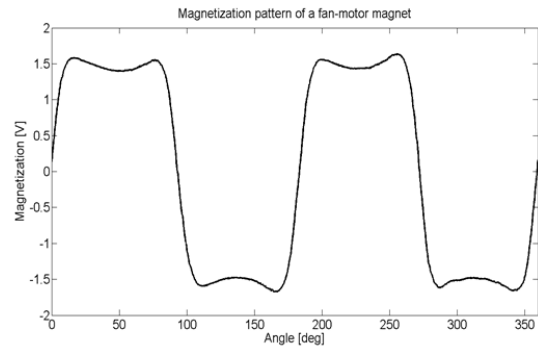


Figure 2: The magnetic flux density measured in volts by a Hall effect sensor located 0.5 mm from a freely rotating four-pole bonded magnet mounted on the rotor of a DC-motor used to drive a computer fan.

2. THEORY

Although emphasis will be placed on the functionality, from a production standpoint, of the magnetizer developed here, the electromagnetic theory involved will be dealt with briefly in terms of a quick overview of the theory of magnetization of materials, as well as a short account of the magnetic properties of different materials, with the aim of providing a basic understanding of how the machine works.

2.1. MAGNETIC PROPERTIES AND MAGNETIZATION

Materials that can be affected by a magnetic field can be divided into different groups, depending on their properties in this respect, those that are affected the most being termed ferromagnetic materials, a group to which above all iron, nickel, cobalt and certain rare earth elements and also various types of minerals and alloys belong. When a ferromagnetic material is exposed to magnetic fields which are externally applied, magnetic domains are formed due to various alignments of the magnetic carriers being created, in contrast to the often random orientation of the spin characteristics of the electrons. When the external magnetic field is removed, either the orientation of the magnetic domains returns to or assumes a random orientation, or the material remains to some extent magnetized, the latter being termed a hysteresis effect. Materials differ in the ability they have to retain the orientation of the magnetic domains they were given while magnetized. The highest degree of magnetization it is possible for a material to retain after the external field is removed is termed the *remanence*, B_r . Materials having a high level of remanence are termed hard magnetic materials. These can be used as permanent magnets. Most ferromagnetic materials have a low degree of remanence and are thus termed soft magnetic materials. They are used for shielding low frequency magnetic fields and also as magnetic flux conductors in electromagnetic components of most types, as taken up further in section 2.2. [4]

A good permanent magnet should produce as large a magnetic flux per weight unit as possible. Still more important is that it be stable in terms of its resisting demagnetization. Just as a material of this sort can be magnetized, it can also be demagnetized if it is exposed to a sufficiently strong magnetic field, opposite in direction. Magnetization is a nonlinear process, one that behaves in a manner similar to the hysteresis loop shown in Figure 3. The remanence flux at the point of intersection between the curve and the y-axis in the figure is marked. A magnetic field of certain strength needs to be applied in order for the flux to be produced, the presence of a still stronger field having no additional effect on the magnet. To demagnetize the saturated material completely, a negative magnetic field of a particular strength, termed the *coercive force* H_c , is required, marked in the graph at the point which is the intersection between the magnetization curve and the x-axis. The grey area in the figure, enclosed by the lines connecting the origin, B_r and H_c represents the active area of a stable magnet. The *energy product* BH_{max} is a measure of the quality of the magnet. It represents the maximum energy the material can supply to an external magnetic circuit. It is the highest absolute value of the product of H and B along the curve extending from B_r to H_c . [4]

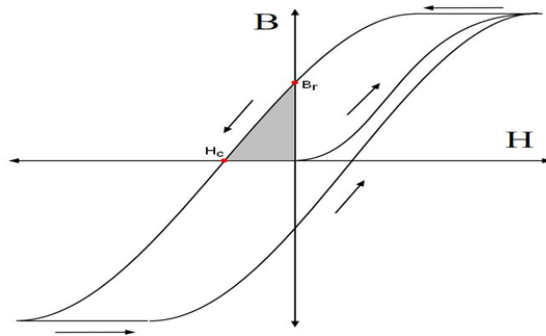


Figure 3: A typical magnetization curve, H being the magnetic field applied and B the magnetic field which is retained.

The magnetization curve is dependent upon the temperature. The application of heat and of a strong negative magnetic field is the most effective way of demagnetizing a material. If a magnet is exposed to high temperatures, its sensitivity to demagnetization increases. If the temperature exceeds a certain limit, called the *Curie temperature* T_c , the long-range ordering that creates the magnetic domains suddenly disappears, all the magnetic properties being lost. [4]

2.2. MAGNETIC MATERIALS AND MANUFACTURING

Despite there being a large number of different materials that can serve as permanent magnets, only few of these are used to this end on any large scale. There are four most frequently used groups of materials of this sort: neodymium iron boron, samarium cobalt, AlNiCo and ferrite. The composition of the materials within such a group or type can vary, depending upon the properties required.

Neodymium Iron Boron (NdFeB), which is the most powerful type of magnet material available on the market, its being highest in terms of the maximum energy product, is the material that the magnetizer will be used for primarily. It has become highly popular on the market because of its high remanence and coercivity levels, together with its reasonably low price per flux unit, yet it is sensitive to high temperatures. [6] NdFeB magnets, which are manufactured in sintered form, have a maximum energy product of almost 400 kTA/m, the polymer-bonded forms being in the range of 40-120 kTA/m, depending upon the manufacturing method involved.

The manufacturing of sintered magnets is a multi-step process. It starts with the materials being alloyed in vacuum before being crushed into powder. To form the magnets, the powder is subjected to a pressing operation that takes place while it is exposed to a magnetic field so as to align the different magnetic domains in the desired direction, important for producing good magnets. The pieces are sintered then under controlled conditions to form a brittle, oxidation-susceptible material before it is machined to correct shape by use of diamond tools, its finally being coated by a protective layer, often of zinc or nickel, for example. The magnets are anisotropic, meaning that they can only be magnetized satisfactorily in the pre-oriented direction. [7] The magnetization of NdFeB magnets should first be carried out after machining of it has been completed. This is usually done for stacked batches by means of pulsed electromagnets supplied with energy from a capacitor bank.

Bonded NdFeB magnets can be produced by extrusion, injection molding or compression bonding. Common to all three methods is the blending of fine NdFeB powder with a polymer-binding material before the magnets are formed. The magnets can be produced in complex shapes having a high level of tolerance. They do not require any finish machining but the maximum energy product achievable is considerably lower than that of sintered magnets. How flexible the magnets can be made depends upon their geometry. They obtain isotropic properties, meaning they can be magnetized in any direction, making them excellent for use as multi-pole magnets. [7]

Although **Samarium Cobalt (SmCo)** magnets are similar to those of NdFeB and they can be manufactured in the same way, the price for them is considerable higher. The energy product at room temperature is only about two thirds that which NdFeB magnets have, but at high temperatures they are more stable than the latter and for certain applications they are more powerful. Because of their high price, SmCo magnets are only used for special applications. [6]

AlNiCo magnets, composed of aluminum, nickel and cobalt, are the most temperature-stable type of magnet but suffer from low coercive force and are mainly used in rotating machinery. AlNiCo magnets, produced by casting and sintering, become hard and brittle. [6]

Ferrite magnets are composed of iron oxide together with barium and strontium. Their low cost, together with their fairly good magnetic properties, make them popular in many applications. Magnets of this type, which can be produced by sintering, often go under the name of ceramic magnets because of their hard and brittle character, but they can also be produced in bonded form. [6]

Soft magnetic materials are often used to help structure the magnetic fields needed in various electromagnetic applications. Using them may also amplify the flux density enormously, by a factor several thousand in size. In electric motors and transformers of almost all kinds there is iron of some form for closing the magnetic circuit and increasing their efficiency, either as separate pieces, as laminates or as (soft magnetic) powder composites, SMC.

For magnetic circuits, the relationship between the magnetomotive force F applied, measured in ampere-turns, At , the magnetic flux ϕ and the total magnetic resistance, termed reluctance R , is a very simple one, shown in equation 1.

$$\phi = F/R \quad (1)$$

The reluctance here is related to the permeability of the materials used in the magnetic circuit, the length l of the circuit, and the cross-sectional area A , in the manner indicated in equation 2.

$$R = l/(\mu \cdot A) \quad (2)$$

The magnetic flux density B , which is the quantity most important in connection with magnetization, is the ratio of the flux to the area involved.

$$B = \phi/A \quad (3)$$

3. DESIGN OF THE MAGNETIZER

3.1. SPECIFICATIONS TO BE MET

A goal involved in developing the magnetizer was to be able to magnetize to their saturation point all four major groups of magnets described in previous section. AlNiCo and ferrite magnets are easy to magnetize due to their low coercive force, while NdFeB magnets require magnetizing fields in the order of 3 T to become fully saturated. SmCo magnets can need flux densities as high as 4.5 T to achieve this. It is very costly to produce stationary magnetic fields as strong as would be required here, yet the needs in question can be met rather simply by use of pulsed electromagnets.

Another goal pursued was that of the magnetizer enabling there to be a variety of shapes and sizes of the objects that are to be magnetized. Since the overall goal was to create a tool able to produce whatever type of magnet was desired, it was highly important that it also be able to function adequately if the type of magnets to be produced should change. Demands that would need to be met would include the magnetizer being able to magnetize any type of material that could be involved, regardless of geometry of the magnets produced, that the spatial and field-strength accuracy of magnetization needed can be achieved, and that it be able to produce magnets having any type of magnetization pattern desired. The magnetizer would need to function as any other type of CNC machine would, in the sense of the result being a function of the computer program steering it and not to any appreciable extent of chance factors that might be present.

3.2. GEOMETRY

In terms of equations 1-3, high magnetic flux densities are achievable by use of a horseshoe-shaped iron yoke having an air gap just large enough to allow the material that is to be magnetized to fit, and having electric coils that encircle the core. Since the iron core would be saturated at magnetic flux densities of 1-2 T, which is far below the 4.5 T level, they would require that the yoke have a cross section larger than the target area so as to not lose permeability and to avoid field leakage. Thus far, the magnetizer developed shows strong similarities to magnetizers of other types, such as those used in tape recorders and in hard drives, in which the magnetic field is limited to a rather small area. One of the most marked differences between this magnetizer and other ones is the considerably higher magnetic field-strength level of the present one. Another major difference is that here the material is to be magnetized in its entire volume and not simply on a thin surface layer, a matter which places special requirements on the magnetizing head, so as to be able to achieve a high and well-defined magnetic field strength level in the target area and nowhere else, except in the yoke. The core is composed of SMC, sold as Somaloy®, the ends being surrounded by copper in the form of hollow cones or pyramids having small openings at the top. The pieces of copper employed are sliced in the middle and are insulated from each other by a thin layer of varnish on their

surfaces, to prevent eddy currents which could result in a significant damping effect on the system from circulating there. The cones function in such a way that the magnetic field produced by a short pulse induces eddy currents in the copper, the direction of which accords with Lenz's law, these currents counteracting the magnetic field through preventing it from passing through the metal, directing it instead towards the opening in which the workpiece is placed. This method only functions effectively for relatively short pulses, but under such circumstances it serves to concentrate the magnetic field to the occurrence of rather well-defined shapes, similar in their geometry to that of the hole, such that configurations of different forms can only readily be achieved by changing the cones.

To enable objects of varying geometry to be magnetized in the machine, it was constructed so as to be adjustable in all directions that variations in geometry could call for. At the same time, it was built to be sufficiently robust, using a brace of solid steel to resist the rather strong forces that act on the SMC yoke during magnetization. The core consists of two overlapping pieces of SMC, the positions of which can be adjusted so as to make it possible to magnetize materials of differing thickness. The construction is held together by a large screw that connects the solid parts, which contain inserts of differing size.

Since the positioning system for the workpiece in the magnetizer can be designed for either linear or rotating movements, the best solution here is not obvious but depends on the geometry of the magnets. Since having curved magnets for the motor was a primary aim in constructing the magnetizer, the system selected was a rotating one, the sensors being placed on an adjustable arm on the side of the motor opposite to that of the magnetization head, a solution similar to that of a machine used to magnetize high-precision multi-pole magnetic encoders.[2]

4. CONTROL SYSTEM

The machine is controlled by a PC using the graphical programming language LabView. The program allows measures obtained to be monitored, settings to be adjusted and magnetization patterns to be specified. The PC communicates with the driver that controls the servomotor, which in turn rotates the workpiece by means of RS232. A data-acquisition card, DAQ, is used as an interface between the computer and both the magnetization system and the sensors. The motor driver provides the computer, in real time, information regarding the motor, such as its position and speed, the current, etc. Measurements by the DAQ of the radial and tangential magnetic fields of the hall sensors provide feedback concerning magnetization. Measurements are also made of the DC-bus voltage of the discharge capacitors, as well as of the current through the coils, etc. The DAQ is also used to send out reference pulse shapes to the electronic magnetization system and provide signals concerning the water cooling system of the power-electronics, and later on of the coils. Figure 4 presents a schematic diagram of setup of the machine.

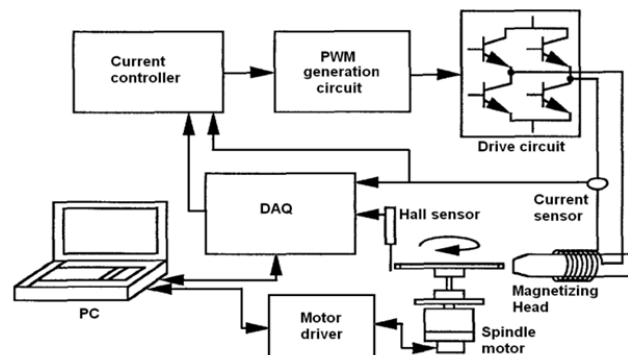


Figure 4: A schematic diagram of the different parts of the magnetizer.

An analogue hysteresis controller for achieving the desired shape and amplitude of the magnetization current was also developed. It compares a reference signal from the DAQ with a signal from a current transducer, enabling a pulse-width-modulated signal to be sent out by way of drivers to a power electronics full-bridge consisting of IGBT modules. Since it is not intended that the system switches to keep the current level at zero, the power electronics is only activated while the reference current is being sent out. The adjusting of the switching frequency to a level of less than 10 kHz is determined by the current derivative, which is related to the inductance of the coils, the capacitor voltage and the hysteresis band.

As can be seen in Figure 3, magnetization is a highly nonlinear process. It also differs from one type of material to another and is dependent upon the temperature. It is thus difficult to model and virtually impossible to map the control signals to the values measured. To achieve the degree of magnetization desired, the difference between the

setpoint and the signal level measured can be determined and an individual PI-controller be assigned to each of the steps involved. Since magnetization is a rapid process, no counteracting derivative value in the controllers is needed, but obtaining integral readings is important for being able to arrive at the setpoint. The PI-controller is implemented using standard procedures of a classical anti-windup type based on a saturation model, as shown in Figure 5. For each revolution, the parameter setup obtained by the controller is saved for the next revolution. Since the magnetization process has a very marked hysteresis effect, the integral part of it can be a problem when the measured signal passes the point aimed at. So as to avoid unnecessary and time-consuming demagnetization, a logic function is used to set the integral part to zero when the sign of the control error and the integral part coincide. A resetting of the integral part under appropriate conditions prevents the system from overshooting appreciably, saving considerable time. At the start, all the PI-controllers are tuned in the same way, although a better approach would probably be to assign the values for the control parameters on the basis of the setpoint and type of material involved.

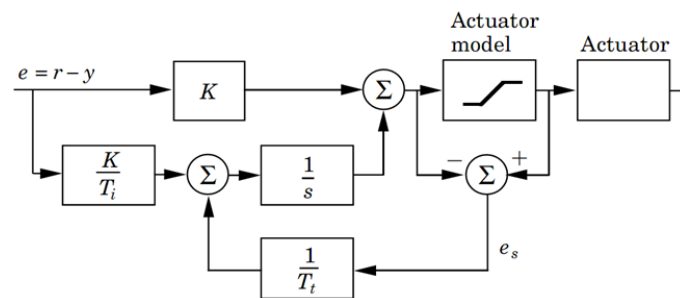


Figure 5: A PI-controller using an implementation of a classical anti-windup type. [8]

5. EXPERIMENTS

The experimental setup is shown in Figure 6, in which a non-closed workpiece made of bonded ferrite can be seen. Since it is costly to produce large tube-shaped magnets in only small volumes, cheap magnet band having cross section of 3 by 12 mm, sold on rolls, were selected as workpiece here. The bands were formed to the proper shape by a cylindrical die and were temporarily glued to the polymer holder.



Figure 6: Photograph of the magnetizer.

The experimental task is that of magnetizing the workpiece with use of an 8-pole sine pattern spread out over an entire revolution of the magnetizer. The pattern selected is one of rather small amplitude as compared with what the magnetizer is capable of. Also, because of the Hall-effect sensors not being calibrated, of the exact value of the expected magnetic field strength not being known and of the feedback only being based on the radial magnetic field, the tangential dimension is temporarily ignored. The step of largest size needed to achieve satisfactory magnetization has not yet been determined, but movements that are too large result in a distinct pattern of superimposed steps. Intuitively, the largest step size would appear to be limited by the width of the magnetization

area, in the present case the workpiece having a diameter of 150 mm and a head geometry of 5 by 5 mm, which results in steps of 3.8 degrees each.

During the magnetization process, the user is provided by the PC with a reference set of current waveforms and is free to choose basically any shape for it. How the magnetization is affected by the shape of the pulse has not yet been tested in any comprehensive way. Half-sine and triangular waves have been found to be effective and to produce less vibration and noise than either waveforms having large transients, square waves or saw-toothed signals do. For the experiments, half-sine-wave pulses having a duration of 10 ms per shot and the maximum allowed current of 320 A were employed.

6. RESULTS

The experiments were performed using steps of 2 degrees each, or 180 positions per revolution, which at the very slow speeds that have been employed means 4.5 minutes being required per revolution. The effects of the speed of the magnetization process have not been investigated thus far, but the question of how adequate synchronization and a high degree of positional accuracy can be achieved has been studied. Since the pulse discharge can create strong disturbances, measurement and magnetization are carried out with a small time shift. The magnetization current is measured using the reference waveform as a trigger, allowing the pulses to be monitored in real time and saved for further analysis. Figure 7 shows the current during a single pulse having a peak current of 140 A.

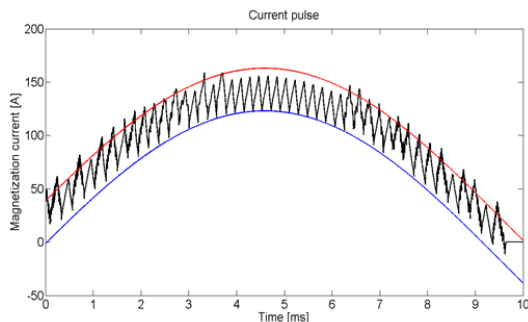


Figure 7: A graph of the magnetization current during a pulse, the two extra curves indicating the hysteresis levels.

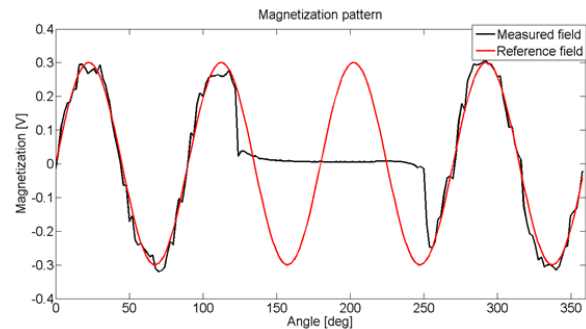


Figure 8: Magnetization, showing the reference pattern and the measured pattern. No workpiece is used at the position angles of 140-240 degrees, hence measured values are zero here.

During the first revolution of the magnetization, no pulses are sent out, only measures of the magnetic field being obtained and being saved for the controller. After one or two additional revolutions, a rather satisfactory shape of the magnetization that is aimed at begins to appear. At the start, the magnetization has a strong effect on the field that is measured, but when the control error becomes smaller, the process becomes slower. Figure 8 shows the measured magnetic field and the reference field after 20 iterations, rather conservative PI parameters being employed. Although the results show a clear relationship between the measured pattern and the reference pattern, it is not yet perfect. Some of the regular superimposed distortions could be identified as stemming from leaks in the fields, leaks that are produced by the magnetizing coils and that could be eliminated by the mounting of steel plates along the workpiece and around the outer parts of each coil to shield these from the copper cones.

The leakage created does not appear to be the only source of error, but a comparison of the waveforms that were found with the magnetization of the positions in question suggests that the ripples that the pulses produce can affect the easily magnetized ferrite material, especially when rather weak currents are used during the final adjustments.

7. CONCLUSIONS AND DISCUSSION

The magnetizer that was developed cannot be evaluated adequately on the basis of only a few experiments, but it can be concluded that the principle involved works in the basic manner expected, although there are major differences between ferrite and NdFeB magnets in the level of field strength required to magnetize them. No specific goal for accuracy was set prior to developing the magnetizer, partly because it was difficult to know how accurate the magnetization needed to be in order to fulfill its purpose and partly because the accuracy can be improved stepwise through fine tuning. There is much that remains to be investigated, such as how different types of materials

behave, how the size of the air gap affects the pattern achieved and how effectively the magnetizer deals with thicker workpieces. Also, different geometries of the magnetization head and how consistent the results are with various simulated models not yet considered need to be evaluated.

Other machines used to produce multi-pole magnets can be seen as far less flexible than the magnetizer developed here. They also lack feedback, as well as the programmable reference patterns found in the present magnetizer, which thus provides many new opportunities. A greater variety of materials and geometries can be magnetized in a satisfactory way here in one and the same machine than appears to be possible with use of other ones. A quality measure of the magnet is also generated automatically. In addition, the magnetizer can compensate for minor material defects caused by the molding, casting or sintering process. At the same time, a drawback of the machine is that of the costs involved, which are directly related to the time needed for producing it. This prevents its present use on a large scale. After certain tuning based on modeling or adaptive algorithms, it can be expected to go considerably faster than it does at present, and the number of revolutions required for magnetizing a workpiece can probably be reduced to only 2-3. If the magnets to be produced are to consist of bonded material, a more production-friendly method would be the use of a straight production line designed for band magnets, use possibly being made of a series of Hall-effect sensors and magnetizing systems, located in succession. Such an approach would eliminate the batch problem. The band could then be cut to the right lengths and be bent into appropriate shape before being attached to an electric motor of the type shown in Figure 1, for example. For linear units, the yoke could be constructed in a simpler way, since both halves could be fixed to the base instead of having the one half levitating above the rotating plate. This would also allow a magnet of smaller diameter to be employed.

Although the magnetization pattern and the use of multi-pole magnets have been of particular concern here, another area of possible interest is that of the magnetizing of ordinary sintered two-pole magnets. Since sintered and above all plated material conducts electricity, eddy currents are induced during pulse magnetization, which distorts the uniformity of the magnetic field. If this problem could be solved by use of small magnetization windows in which a linear magnetizer was able to carry out magnetization rather quickly, this would be a major gain. As things presently stand, the magnetizer goes to the next position, it stops there to measure the degree of magnetization achieved and to send out a pulse before it continues on to the next step. If the pulses were made short enough, the workpieces could move continuously at a constant speed. This would save a considerable amount of time.

At present, the magnetizer can achieve basically any pattern of magnetization in a given direction. At the same time, adding an extra dimension in which the magnetization head can move up and down is fully possible. Applications for a magnet of this type are clearly to be found, in the area both of electric machines and encoders. To produce electric motors with only one magnetic element is competitive from the standpoint of performance, size and production.

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