Permanent Magnet Excited Brushed DC Motors

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Abstract—Brushed dc motors excited with permanent magnet material can be found in a wide range of applications. The largest market segment for this type of motor and their predominant use is found in the low-power range. New developments in the area of high-energy permanent magnet material offer the opportunity of miniaturization and promise a cost-effective design. Starting with a brief summary on the permanent magnet material, special design considerations and typical constructions followed by motor applications of radial and axial field configurations will be discussed. Particular attention must be paid to the construction of the permanent magnet excited brushed dc motor with respect to the manufacturing costs. Common winding arrangements and cost-effective lamination constructions are presented to illustrate different manufacturing techniques and possibilities.

I. INTRODUCTION

MOTORS are essential parts in a large variety of industrial products and domestic applications. To list only a few, there are motors in the kitchen, washing machines, dryers, in computer hardware, auxiliary drives for the automotive industry, and high-quality machine tools drives. Although the power range extends from a single watt to machines on the order of 100 kilowatt, the predominant use of permanent magnet motors is found in the low power range. Typical applications of brushed dc motors are in the low voltage range from 12–24 V, as found in cost-effective constructions for auxiliary drives in the automotive industry. These drives are so prevalent that as many as 80 single drives are installed in each of today's luxury cars. Applications operated from 110/220 Vac have the additional costs associated with the ac/dc conversion. In addition, due to the lack of the field winding, the elimination of radio interference is expensive compared to an universal motor.

Although the motor requirements mentioned above can be met either by brushed or brushless permanent magnet motors, the brushed motors tend to be less expensive. In recent years the power electronics required for brushless designs have been decreasing in cost, the brushed motor will still maintain a considerable market share.

New types of permanent magnet materials, such as plastic bonded rare earth components, offer the ability to design electromagnetic energy converters with complicated shapes [5], [8], [12], [13], [16]. Therefore, the construction topologies vary to a large extent. For many applications, a permanent

magnet dc motor can be designed which is smaller, lighter and more efficient when compared to the equivalent wound field dc machine. The achievable size reduction is strongly determined by the choice of the magnet material which can offer a wide range of magnetic, mechanical, and thermal properties. The market for permanent magnet motors in automobiles is dominated by ceramic ferrites, because component cost generally overrides any performance considerations [9]. The unique properties of rare earth magnets are high energy density, high flux density, and high coercivity. The wide variety of manufacturing and processing methods of rare earth magnets which result in mechanical and thermal stability have opened up additional applications in consumer products. It follows that machines built from these materials are showing significant improvements in the machine performance. The benefits are low moment of inertia, high power/weight ratio, high efficiency, especially important in battery supplied systems, better dynamic response, reduced volume, and a high torque overload capability.

II. PERMANENT MAGNET MATERIAL

Electromagnetic, thermal, and mechanical properties of the permanent magnet material used inherently influence the specific construction and design of an electromechanical energy converter. Therefore, in this section the properties of the various materials are described. Permanent magnets, known as magnetically hard material, are materials that retain their magnetism after the removal of an external magnetizing field.

Sintered and cast AlNiCo alloy magnets were the first commercially available materials. Nowadays their use is decreasing. The main constituents are aluminum, nickel, cobalt, and iron together with a number of other elements. They are alloyed and cast. The resulting casting is heat-treated to develop the magnetic properties. AlNiCo can also be sintered and this process is particularly suitable for small parts. All AlNiCo magnets feature a high remanent flux density B_R, excellent thermal stability and elevated temperature performance. The standard grade is anisotropic with orientation along the length. For certain applications, isotropic grades are also available. Because of its metallic composition, AlNiCo is a good electrical conductor. The really weak point of this material is its low coercivity H_C making it very susceptible to demagnetization by external fields.

Sintered ferrite magnets became available in the 1950s. This type of magnet is produced by the powder metallurgy process from a compound of ferric oxide and carbonate of either barium or strontium. The sintered compact is very hard and brittle and is often referred to as a ceramic. The features of this type

of material are cost effectiveness, good corrosion and chemical resistance, a wide range of magnetization possibilities and a wide operating temperature range up to 250°C. Ferrites are very good electrical insulators. Therefore, eddy current losses inside the magnet caused by time-varying demagnetizing fields do not play a significant role.

In the 1960's a magnetic alloy of cobalt with the rare earth element samarium was discovered. This material produces a strong magnet with a linear demagnetization curve and thus a strong resistance to demagnetizing fields. This quality is a major advance in magnetic materials. The energy density increased by a factor of three when compared to classical magnets with the SmCo$_5$ grades and later by a factor of six when the SmCo$_{17}$ phase was discovered. Those grades became commercially available in the 1970's. The material is produced by the powder metallurgy process and the magnet is field oriented during pressing. The sintered compact is both hard and very brittle. The features of this material are high remanent flux density B_R and high coercivity H_C, which means high resistance to demagnetization and good corrosion resistance. The material is anisotropic and the direction of magnetization is usually in the direction of the thickness of the sample. SmCo is electrically conducting. The weakness of this type of permanent magnet is the careful handling required to prevent chipping and breaking. Therefore, specific assembling techniques are necessary to build up the electromagnetic device. Furthermore, it is very expensive and requires the use of the strategic materials samarium and cobalt that are not commonly available on the market.

The neodymium iron boron (NdFeB) magnets offer the highest energy density presently available from various manufacturers. Discovered by Sumitomo Special Metals Company and General Motors in 1983, who hold the patents for the alloy, the production route is a powder metallurgy process similar to that of SmCo. The main features of this magnet material are its very high remanence B_R and coercivity H_C and its good machinability properties. It is mechanically stronger, less liable to chipping, has lower costs and density compared to SmCo alloys. This enables further weight reductions by substituting NdFeB in SmCo applications. The material is anisotropic and its magnetization is usually in the direction of the thickness of the magnet. It is electrically conducting. The main weaknesses of NdFeB lie in its strong temperature dependent magnetic properties caused by its low Curie temperature and its tendency to corrosion. With additions of dysprosium (Dy) and/or Co, the material becomes more temperature stable, but simultaneously the good properties are reduced when compared to those of SmCo. In addition to this, the material costs are rising. Therefore, only specific commercial applications can be found with this type of magnet.

The grades of ferrite, SmCo and NdFeB are also available as plastic bonded components. In Fig. 1, typical demagnetization characteristics of the mentioned types of permanent magnet material are plotted. To chose a proper material for a specific application, some general physical selection criteria can be given [6].
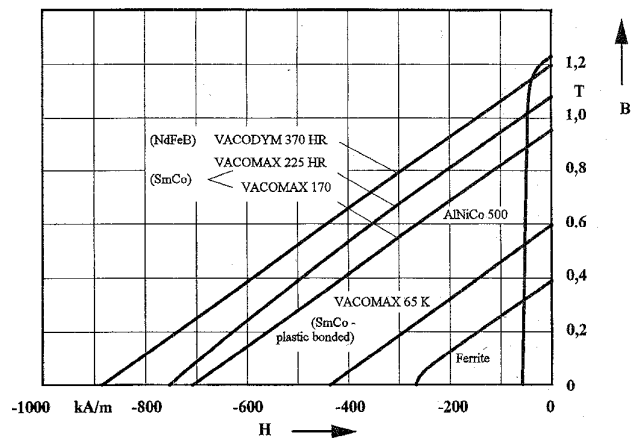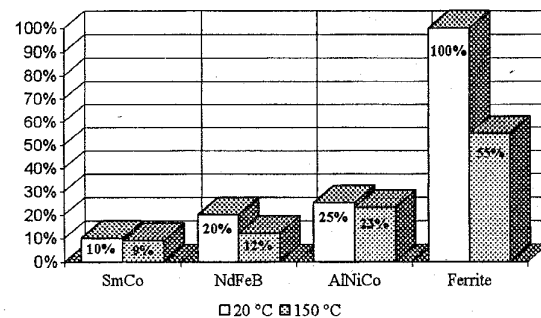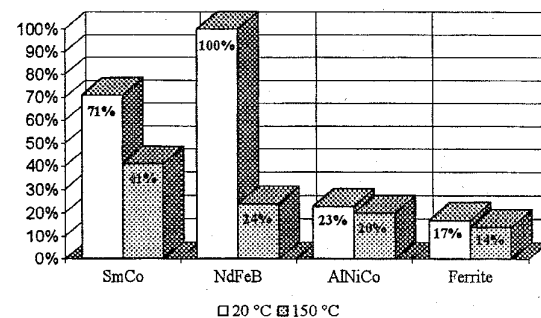

Fig. 1. Typical demagnetization characteristics at room temperature 20°C (Vacuumschmelze catalogue M054; 07/89).

(a)

(b)

Fig. 2. (a) Energy per magnet cost referenced to ferrite [6]. (b) Specific energy referenced to NdFeB [6].

- A high value of energy product $(B \cdot H)_{max}$ results in a compact electromagnetic core at a given output power.
- A high value of remanent flux density B_R results in high forces and torques.
- A high value of coercivity H_C results in high demagnetization resistance of the magnet.
- A straight-line characteristic of the demagnetization curve $B = f(H)$ results in low losses during dynamic operation.

The given criteria to select the best material for a specific application are only taking the technical requirements into
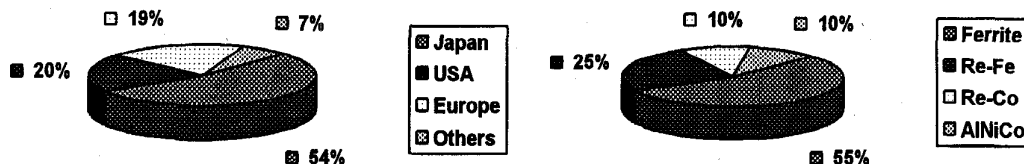
Fig. 3. World permanent magnet production [16].

account. Material expenses play an important role in the selection as well. The temperature dependence of the costs and the magnetic properties can be taken from Fig. 2. At elevated temperature NdFeB loses its dominant magnetic characteristics. The conclusion of this diagram shows clearly that there are two main criteria for the selection [6]:

- economical efficiency, i.e., energy per cost;
- technical requirements, i.e., energy per weight.

To identify the importance of the permanent magnet materials, Fig. 3 shows their world production [16]. The past years have also shown a trend toward the increasing use of rare earth components.

New developments in the material science toward temperature stability, processing costs and advanced magneto-mechanical properties have resulted in investigations of nitride permanent magnet alloys [16]. Those investigations in the laboratories are still too recent to have produced reliable data and probes of the material for general users are not yet available. However, the small amount of existing information shows promise for the future development of permanent magnet motor technologies.

III. MAGNETIC DESIGN CONSIDERATIONS AND CONSTRUCTIONS

The demagnetization characteristic of the various types of magnet material have significant influence to the construction of the electromechanical energy converter [17]. In Fig. 4 a general plot of the second quadrant of the BH-curve is given. Without an armature current the intersection of $B = f(H)$ with the load line leads to the steady state no-load operating point A_1. The demagnetizing field strength H_d, due to a current inside the armature winding, shifts the intersecting point to the operating point A_2. To avoid irreversible demagnetization of the permanent magnet, the field strength inside the magnet material must be greater than the knee field strength H_{knee} [4], [5]. If H_M and B_M are the field strength and flux density inside the permanent magnet and with the assumption that there is no leakage flux the load angle α is defined as

$$\tan \alpha = \frac{H_M}{B_M} = \frac{\delta}{h_M \mu_0} \qquad (1)$$

with δ the air gap length, h_M as the magnet thickness, and A_M the magnet area is equal to the air gap area A_δ facing the permanent magnet.

Considering an AlNiCo material curve, a small value of the load angle is needed to avoid irreversible demagnetization
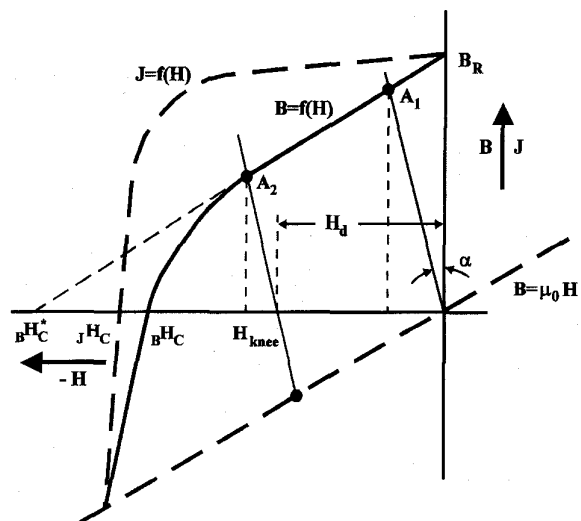

Fig. 4. Behavior of permanent magnets in a machine.

under load conditions. Therefore, the air gap must be small and the height of the magnet must be large. This causes a large volume of permanent magnet material and consequently large overall dimensions of the dc motor construction. Furthermore, an additional winding has to be embedded into the motor to magnetize the AlNiCo magnet after assembling. Otherwise the material would be demagnetized with an open magnetic circuit. To prevent irreversible demagnetization during operation under load conditions, specific flux paths made of ferromagnetic material have to be constructed to lead the flux caused by the armature reaction away from the magnets. If air gap magnets are used, ferromagnetic pole caps are glued on top of the permanent magnet. Therefore, nowadays only special applications employ permanent magnets made of AlNiCo.

Compared to AlNiCo, the ferrite magnets have a low remanent flux density B_R. Due to the coercive force H_C of ferrites, the load angle can be larger and an open magnetic circuit does not demagnetize the material inside. This offers the opportunity to magnetize the magnet before assembling the motor.

The rare earth component magnets SmCo and NdFeB have high values of remanent flux density and coercivity. Therefore, those grades are very stable during operation in external demagnetizing fields. Special attention has to be paid to NdFeB at elevated temperature in order to prevent irreversible demagnetization. Due to the high remanence of rare earth magnets, small air gaps and thin magnet plates or segments can be used.

1) Flux Concentration Techniques [5]: To obtain a high value of the flux density in the air gap, special flux concentration techniques can be applied. If A_M is the magnet surface and A_δ the air gap area facing the magnet, the air gap flux density can be written as

$$B_\delta = \frac{B_R}{\mu_M \dfrac{\delta}{l_M} + \dfrac{A_\delta}{A_M}} \qquad (2)$$

with $\mu_M = B_R/(_BH_C^* \cdot \mu_0)$ as the incremental permeability of the permanent magnet. Equation (2) illustrates the use of a possible flux concentration. If A_M is large compared to A_δ, this results in an elevated value of the air gap flux density. An overhang of the magnet poles is the simplest way to increase the air gap flux, since a 20% overhang raises the flux density by approximately 15%. This technique is used in applications with ferrites only.

2) Two-Component Permanent Magnets: The field strength generated by the armature current in an electrical motor causes no-load operating point A_1 to move to the point A_2 (Fig. 4). If a motor is considered, this results in a demagnetization of the permanent magnet at the outgoing edge and strengthening at the incoming edge of the magnet pole. High short circuit currents at start of operation may result in a partially irreversible demagnetization of the magnet material. To avoid this, two different materials can be used to form one magnet pole pitch, a permanent magnet with a high coercive force fixed to the outgoing edge and material with high remanence flux density at the incoming edge. This technique can only be applied in motors with one direction of rotation and it results in higher manufacturing costs.

IV. BRUSHES

The current supply of the armature winding is provided by brushes moving over a commutator. The commutator fixes the armature flux orientation relative to the field generated by the stator permanent magnets. The whole arrangement consists of a set of brush-holders mounted close to the commutator. The brush-holder is a metal box opened at the top and bottom end provided with a spring. Different spring arrangements are possible as shown in Fig. 5. The brush is inserted from the top end of the brush-holder and pressed against the commutator by the spring. In general, the positioning of the brushes can be one of the three ways: radial, trailing or leading. Most applications are equipped with radially oriented brushes (Fig. 5(b)) to ensure performance in both directions of rotation. Nonreversing motors can be equipped with 10–15° of vertical angle inclined brushes (Fig. 5(c)). This can be in either a trailing or leading direction to improve the stability of the brush contact to the commutator. If narrow brushes have to be used the reaction arrangement with a vertical angle of 30–40° is applied in the leading direction. With respect to possible vibrations of the brushes in critical applications the arrangement shown in Fig. 5(a) is recommended.
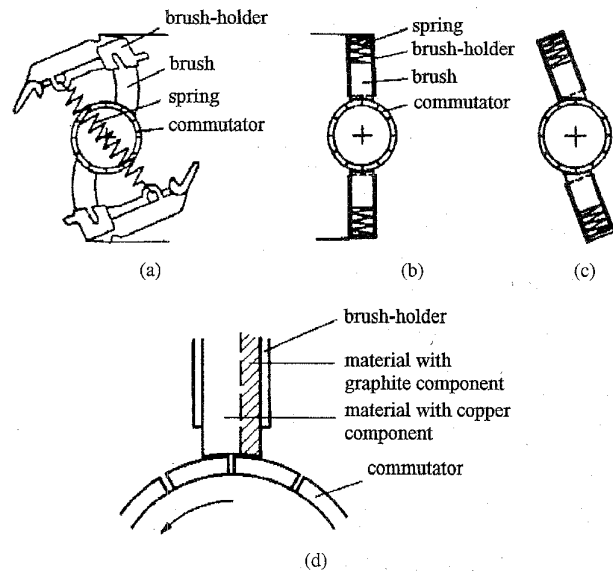

Fig. 5. Brush-holder constructions. (a) Reliable leading/trailing with spring. (b) Radial. (c) Inclined. (d) Two-component brush.

A. Brush Materials

The brush material is usually either natural graphite, hard carbon, electro graphite, or metal graphite. The quality of commutation depends on the brush voltage function. The current density at the outgoing edge of the brush is lower with increasing brush contact resistance and voltage drop. However, this increases the contact losses and results in an elevated temperature of the brushes and the commutator. As a consequence improvements made to commutation result in both a life time and efficiency decrease. Therefore, two-component brushes are used (Fig. 5(d)). What is often done in practice is that the outgoing edge of the brush will be made of a material with a graphite component and so enlarges contact resistance. The remaining part of the brush is made of copper to give a low contact resistance. With this technique, the lifetime of the brushes can be increased by a factor of two.

1) Natural Graphite: A composition of natural graphite and resin leads to a brush with good mechanical properties and therefore is applicable in high speed applications. The low conductivity caused by the resin component results in a good commutation where a high contact voltage drop is necessary.

2) Electro Graphite: Due to their long life time the main applications for electro graphite brushes are high quality large motors with electrical excitation.

3) Metal Graphite: Brushes consisting of metal graphite have a high conductivity. Due to the low contact voltage drop, brushes of this type are preferable in applications with high currents and low voltage, as in automobile starter motors.

4) Hard Carbon: Using hard carbon leads to inexpensive but hard brushes. Therefore, a long life time of the brushes can be expected. The brush wear lies in the same range as the life time of the commutator segments and their insulating material. This type of material is mainly used in motors of

the low power range for low speed applications where the commutation conditions are not very important.

V. MOTOR APPLICATIONS

Advanced technology in manufacturing and computing of the operational behavior of motors based on the electromagnetic field energy conversion has considerable impact on the innovation of many motor driven appliances. Due to ongoing efforts in the development of extended mathematical and numerical tools to accurately predict the electromagnetic field inside a specific device, it is possible to design and numerically optimize very complex motor geometries. Nowadays, the finite element method is the computing tool in a general application range. Various program packages for two- and three-dimensional field computations are available on the software market.

The earliest electrical machines based on the principle of electromagnetic-mechanical energy conversion were axial field machines. However, they were replaced by radial field machines after a short time. DC motors equipped with permanent magnet excitation can be found in a wide field of applications for powers up to 100 kW. The permanent magnet dc motor is accepted for general purpose drives as well as for industrial servo applications.

Permanent magnet excited motors have a linear speed/torque characteristic. The equations for a brushed dc machine can be derived either from the magnetic field or the coupled-circuit viewpoint. The electromechanical coupling terms are the developed magnetic torque T and the induced voltage U_i:

$$T = c \cdot \Phi \cdot I_a \tag{3}$$

$$U_i = c \cdot \Phi \cdot \omega = c \cdot \Phi \cdot 2\pi n \tag{4}$$

with $c = z \cdot p/2a\pi$ and

I_a	armature current;
z	total number of armature conductors;
ω	angular velocity;
p	number of pole pairs;
Φ	total flux per pole;
$2a$	number of parallel winding circuits.

These operations (3)–(4) together with the differential equations of motion of the mechanical system, the volt-ampere equation for the armature circuit, and the nonlinear characteristic of the ferromagnetic parts of the machine and the demagnetization curve of the permanent magnet, describe the system performance of the permanent magnet machine. The armature MMF has definite effects on the space distribution of the air gap flux and the magnitude of the net flux per pole. The effect on flux distribution is important because the limits of successful commutation are directly influenced.

A. Radial Field Type Configurations

This section provides several examples of radial field motors since specific applications require different designs. Various

types of permanent magnet constructions are shown in Fig. 6. The most common design is equipped with radially magnetized magnet shells (Fig. 6(a)). To avoid irreversible demagnetization at startup due to the armature reaction, two component magnets can be used (Fig. 6(b)) or else soft magnetic poles can be fixed to the air gap surface of the magnet shells. In a simple construction, avoiding cogging torques due to the interaction of rotor teeth and magnet pole edges, a diametric magnetized ring magnet can be used (Fig. 6(c)). The diametric magnetization generates a sinusoidal flux density distribution in the air gap. In low cost consumer applications, single magnet constructions can be chosen (Fig. 6(e) and (f)). To obtain a very flat design the variants in Fig. 6(g) and (h) are applicable. Constructions for high quality servo motors equipped with ferrite magnet material have to be designed with flux concentration techniques (Fig. 6(i) and (j)) to generate a higher magnitude of flux density in the air gap to serve a higher torque.

In Fig. 7 two design variants of high-quality industrial servo motors equipped with different permanent magnet materials are shown [10]. Due to the high remanence flux density of $SmCo_5$ or $NdFe_{12}B_5$, a relatively thin magnet arrangement can be used (Fig. 7(a)). Compared to the flux concentration technique used in the construction from Fig. 6(i), this motor design (Fig. 7(b)) is constructed with an additional permanent magnet in each pole gap to achieve an increased flux density in the air gap.

Applications of Radial Field Designs: Mass production of high-quality brushed dc motors equipped with permanent magnet material exists for automotive applications. With the present magnet technology, permanent magnet excited dc automobile starter motors are available up to a power of 2 kW (Fig. 8) [9]. Due to the high costs of rare earth magnet alloys, generally only ferrite materials are used. Compared to the conventional series commutator motor, the inset of a planetary gear offers the opportunity to install a smaller high-speed dc motor equipped with permanent magnet excitation. This results in a reduction of volume and weight of the starter. Very strenuous operating conditions of drives in automotive applications are forcing a careful design. Vibrational accelerations between 50–60 g may occur during operation [9]. Extremely high and also low temperatures ranging from −40°C to 180°C and a corrosive environment demand special attention during the design phase of the electromagnetic circuit with emphasis toward mechanical and magnetic properties. Under cold-start conditions a combustion engine needs 60–100 r/min and a diesel engine requires 80–150 r/min [9]. With decreasing temperature the combustion motor starting torque increases and an elevated starting power is recommended. Therefore, the most important design criterion is the cold-start condition. Due to the temperature dependence of the magnetic characteristic of ferrites, the output torque of the motor decreases as the temperature drops. Combined with the increased counteracting torque of the combustion engine, this may lead to problems at lower temperature.
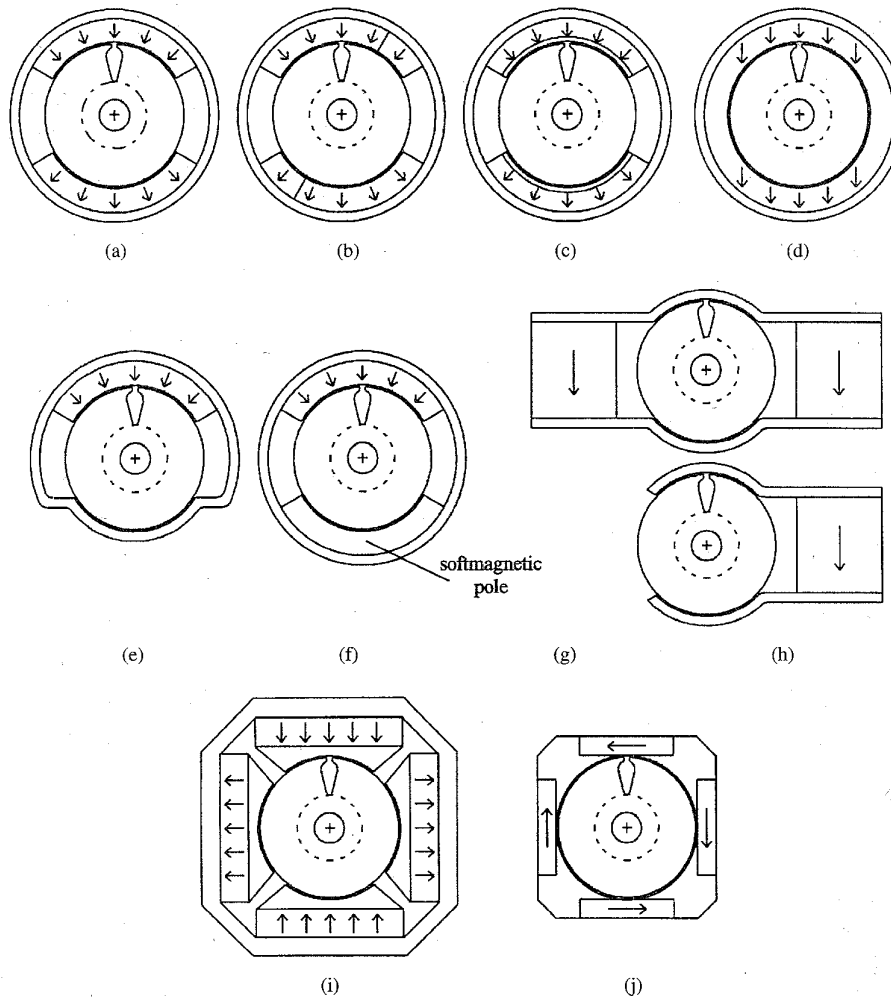
Fig. 6. Typical magnet configurations. (a) Radially magnetized shell design. (b) Two component magnets. (c) Construction with soft magnetic pole shoes. (d) Diametrical magnetized ring magnet design. (e) Flat single magnet construction. (f) Single magnet design. (g) Flat double magnet. (h) Compact single magnet design. (i) and (j) Different flux concentration techniques.

Automotive windshield wiper motors are constructed with a third brush. In this easy way it is possible to provide the dc motor with two different speeds. The third brush generates a braking torque caused by the conductors located below the pole pitch and usually this third brush is also located below the pole pitch (Fig. 9(a)). Therefore, commutation is performed in the permanent magnet field. Using the third brush the starting torque, referenced to the resistance of the armature winding, decreases compared to the operation with two brushes. To increase the starting torque a diode between the third brush and the first brush can be used (Fig. 9(b)). This technique to apply two different speeds leads to a shortened life time of the third brush, increased electromagnetic interference and can therefore be used in low power motors only.

An other variant of a radial motor is the triple T-armature motor which is found in toy applications. This type of motor is manufactured for a very low power operation up to 3 W. The very simple construction of the armature winding is what results in relatively low manufacturing costs (Fig. 11(a)). A

disadvantage of this type of motor is the higher likelihood of torque ripples. Therefore, careful attention to this phenomenon must be paid during the design.

B. Axial Field Type Configurations

The rotor of this type of machine is a disk which moves across the permanent magnet field in such a way that the flux passes in the axial direction. The field exciting permanent magnets can be located at either one or both sides of the stator. With this design the magnetic flux has to pass a large air gap. It appears that with the high energy permanent magnets, the flat shape of the axial field machines is a desirable configuration, especially for applications with axially restricted dimensions. Applications with those requirements can be found in robotics and mainly in computer peripherals.

Applications of Axial Field Designs: A typical servo drive application of an axial field motor is shown in Fig. 10. This type of motor can be found in the power range up to 2.5
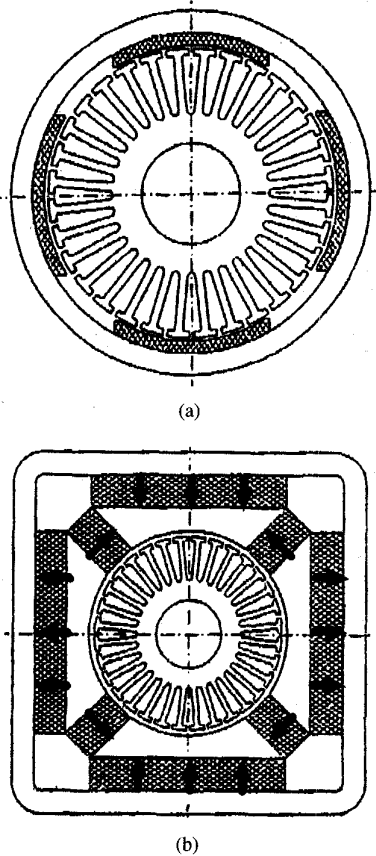
(a)

(b)

Fig. 7. (a) Brushed dc servo motor design equipped with SmCo magnets [10] (ABB). (b) Motor design with ferrite permanent magnet excitation and flux concentration [10] (Siemens).
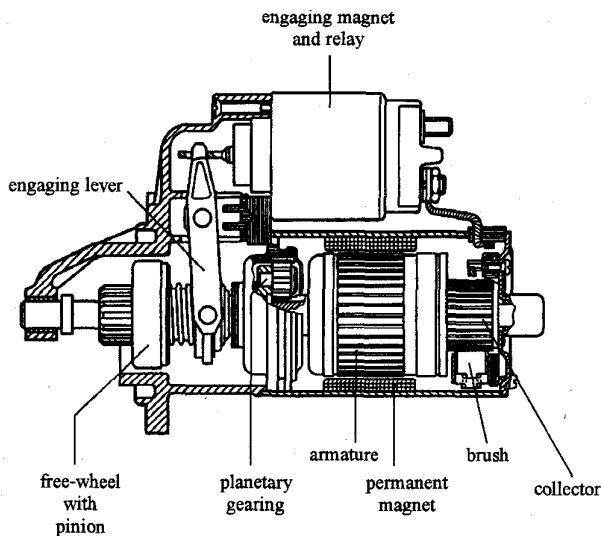

Fig. 8. Starter motor with ferrite permanent magnets [9] (Bosch).

kW [10]. The stator consists of a double magnet system to achieve the magnet height necessary for this type of material, as previously mentioned. The air gap magnets are protected against the armature reaction with soft magnetic pole shoes.
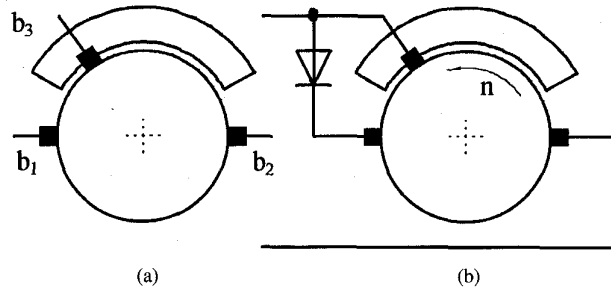

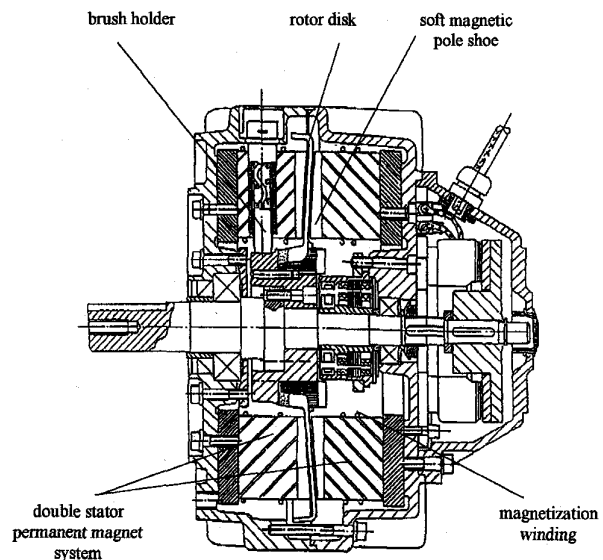Fig. 9. (a) Position of the third brush b_3. (b) Third brush with diode.

Fig. 10. Disk type axial field motor excited with a double stator AlNiCo permanent magnet arrangement [10] (1 kW, 83 V, Bosch).

In this application, the armature rotor disk is equipped with a cylindrical commutator. In general, disk type motors have more than one pole pair due to their construction. To avoid a set of brushes for every pole pair, in applications with low currents the armature is an undulatory winding type. In applications with high armature currents, multiple sets of brushes are used not to violate the current limit of the brushes. AlNiCo permanent magnet equipped machines carry an additional winding wrapped around the magnets to allow magnetization of the material after assembling the whole construction (Fig. 10).

C. Manufacturing Aspects

Particular attention must be paid to the construction of a brushed dc motor for each specific application with respect to the manufacturing costs. To decrease those costs, specific technologies are applied. Cost-effective winding constructions are illustrated in Fig. 11. The winding arrangement of the before mentioned three-T armature motor represents a cost-effective solution for low power products with reasonable operational behavior concerning the torque ripple. Other applications require special fabrication strategies.
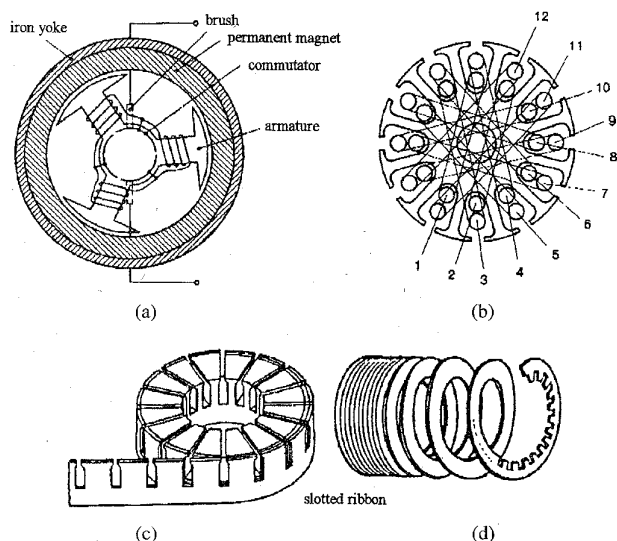
Fig. 11. Armature winding arrangements and stator lamination design for low cost series manufacturing.

A common winding construction, the H-winding [6], is shown in Fig. 11(b). This type of winding consists of an upper and a lower winding layer. A fully automated winding method for manufacturing is possible. The winding consists of two lower, of one upper and lower and two upper winding layers—coils 1 and 2 each with two lower layers; 3 and 4, 5 and 8, 9 and 10, each with one upper and one lower layer; the coils 11 and 12, each with two upper winding layers. Compared to coil wound across the diameter the end-windings of this layout are more regularly distributed. A cost-effective fabrication of the stator lamination for radial and axial flux machines is illustrated in Fig. 11(c) and (d). The punched iron lamination is bent in such a way that it forms the complete slotted stator construction.

VI. CONCLUSIONS

Permanent magnet excited brushed dc motors are applied in many systems. An increasing demand for cost-effective servo motors can be seen with an ongoing trend to substitute the conventional motor systems by permanent magnet excited motor components. The primary market for machines of this type is the low power and low voltage ranges.

With the development of high energy permanent magnet materials such as SmCo and NdFeB alloys, miniaturization of existing devices is possible and has been successfully carried out [3], [6], [7], [18], [20], [24]. However, due to the high costs of those rare earth permanent magnets, the brushed dc machines equipped with ceramic ferrites are still dominating the market.

It is true that with the arguments of flexibility in the control of the motor, frequent maintenance, basic mechanical failure rate and decreasing costs for power electronic components, an increase in brushless permanent magnet excited machines can be witnessed. However, the brushed permanent magnet motors will still retain their applications in the near future.

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