ADVANCES IN STEPPER MOTORS: THE DISC MAGNET TECHNOLOGY

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INTRODUCTION

The tremendous success that stepper motors have encountered over recent years is directly related to the progress of the semiconductor industry. There is an ever-increasing availability of integrated circuits, which make the stepper motor drive electronics easy to realize.

The fundamental advantage of a stepper motor, speed and position control without feedback, is becoming more attractive to industries sensitive to cost, or to overcome the reliability problems linked to the mechanical commutation system of DC motors.

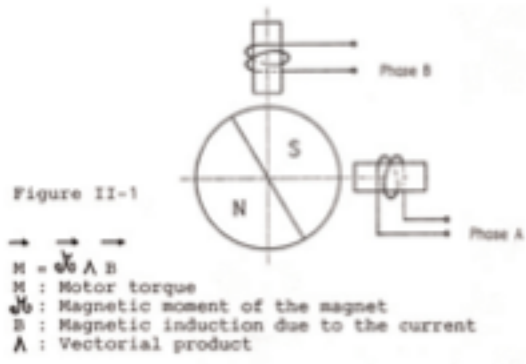
But in some applications a stepper motor can also be the preferred solution, for example if a wide speed range is required.

Several different designs are used for stepper motors. Rare earth permanent magnets, (SmCo and NeFe), offer designers opportunities to obtain performance attributes that rival brushless DC technology.

SALIENT DIFFERENCES BETWEEN A TRADITIONAL BRUSHLESS DC (BLDC) AND A STEPPER MOTOR

Definition of a BLDC and a stepper

The principle of these two motors is identical to a DC motor having its magnet moving instead of the copper. To understand how they operate consider the simple model figure II-1.



<figure II-1>

Conceptual difference between a BLDC and a stepper motor
For a BLDC, the position control is accomplished by utilizing a feedback transducer such as an encoder or a resolver.

For a stepper motor the number of steps/revolution depends on the number of phases and the number of pole pairs. For instance, let's compare a motor having a small number of poles and a motor having a high number of poles:

Motor Having a Number of Poles

Number of stable positions one phase on/rev.	Small	High
Stiffness	Small	High
Commutation/rev. Iron losses/rev.	Small Small	High High
Torque/Watt	Approximately equivalent w/similar designs	Approximately equivalent w/similar designs
Application	DC Motor BLDC	Stepper

A stepper motor will have a high number of commutations per revolution in order to have a high number of steps per revolution. This proves the importance to have a magnetic circuit optimized to take care of the iron losses.

THE DIFFERENT TECHNOLOGIES
Stepper motors can be divided into two basic groups: the first one works without permanent magnet, the second one uses a permanent magnet located in the rotor. Variable reluctance motors form the first group whereas the second one comprises the original permanent magnet motor, the hybrid motor, and the disc magnet motor.

Variable Reluctance Motors

Advantages	**Drawbacks**
Possibility to have a high number of steps per revolution	Poor Performances
No detent torque	Iron losses
Easy to manufacture, low cost design	Reluctance changes vs. rotor position
	Cannot be driven in microstepping mode

The conventional permanent magnet stepper motor (PM)

The rotor of this motor consists of a cylindrical permanent magnet that is radially magnetized. The basic design clearly shows that the direction in which the rotor is going to move (cw or ccw) will depend on the magnetic polarity of the stator poles, hence on the direction of the phase currents.

Figure III-2

<figure III-2>

This two-phase permanent magnet stepper motor (figure III-2) has a rotor with 3 pairs of poles. It will make 12 steps per revolution (2 phases x 6 poles) and have a step angle of 30°. There are no teeth on the rotor.

Practically all conventional permanent magnet steppers are either of the 2-phase bipolar or 4-phase unipolar type (bipolar = phase current changes direction every other step, unipolar = phase current is on or off but does not change direction). If the above diagram is considered a 2-phase motor, then phase 1 consists of coils A and A' and phase 2 of coils B and B'. If it is a 4-phase unipolar motor then coil A is phase 1, coil B is phase 2, coil A' is phase 3 and coil B' is phase 4. In that case, coil A and A' could be combined in one bifilar winding and so would coils B and B ".

Permanent Magnet Motors

Advantages	**Drawbacks**
Cost	Difficulty in having a small step angle
Better performances than VR	Inertia
	Iron losses, no high stepping rate capability

The hybrid stepper motor
In the chapter before we saw the advantages and drawbacks of VR and PM motors. The natural step was to try to keep the advantages of both technologies. The VR can have a small step angle, the PM has better performances due to the magnet in the airgap.

The principle is as shown on figure III-4:

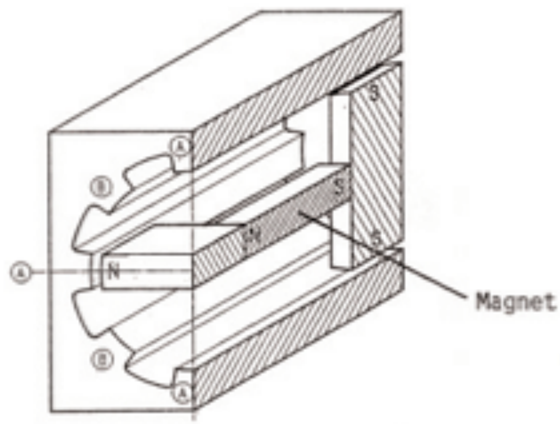


Figure III-4

<figure III-4>

As indicated by its name, the rotor of a hybrid motor has both a permanent magnet and teeth. These will physically modify the airgap as the rotors moves, and therefore the inductance of the phase winding changes with rotor position.

The disc magnet technology
<u>History</u>
Back in the sixties when quartz-controlled watches appeared on the market, Portescap developed a new type of stepper motor to be used for driving the hands of such watches. The motor had to be very small and very efficient. At that time, permanent magnets made of rare earth elements started to be available. Their high magnetic energy made it possible to magnetize a relatively long airgap using a magnet that was actually shorter than the airgap. A considerable research and development effort resulted in the single-phase stepper motor with "thin disc magnet rotor" being used in many millions of watches, and finally leading to the "2-phase disc magnet stepper motor" presented in 1981.

<u>Reminder</u>
We have already evaluated different technologies with their advantages and their drawbacks. The conclusion is clear; a way to improve the design would be to have a PM motor having a high number of poles and a better magnetic circuit. With this goal you will arrive naturally at the disc magnet (DM) technology. But as we will see later this is possible only with the rare earth permanent magnet. In fact this technology is the result of magnet material improvement.

What is a DM motor? Principle:

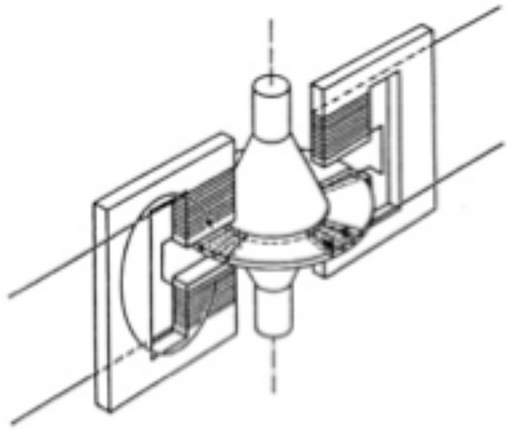


Figure III-5

<figure III-5>

Why does this technology need rare earth permanent magnet and why does it take full advantage of it?

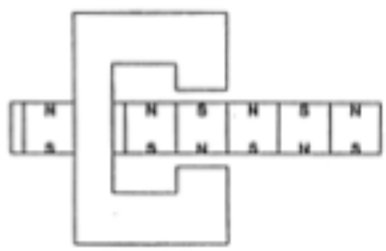


Figure III-7

<figure III-7>

Looking at the magnetic circuit (figure 111-7) we can easily understand that the magnet will have different working points versus its position and versus the flux generated by the winding itself.

For instance, when a pole is inside the airgap, the working point of the magnet on the BH curve is very high and the magnetic induction is at its maximum. When a pole is outside of the airgap, the magnet is in the air and the working point is then very low. It means that you need a magnet very linear in the second quadrant of the BH curve. This is possible with rare earth permanent magnet. Add to this some current in the winding and you have the working point of the magnet covering a wide area on the BH curve.

Let’s consider a basic example (figure 111-8):

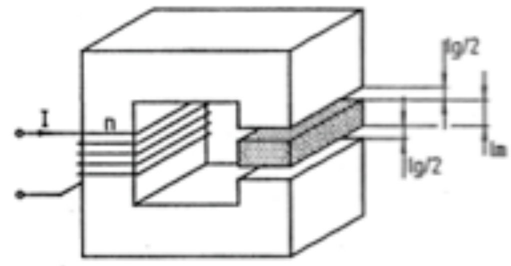
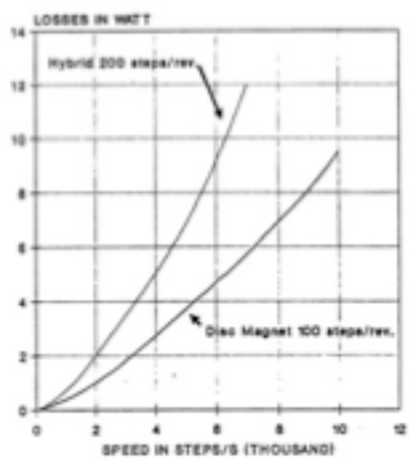


Figure 111-8

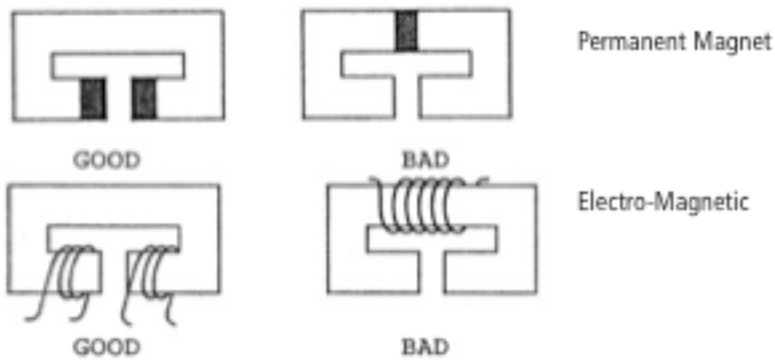
If : L_m Magnet length
L_g Gap between the magnet and iron tooth
B_S Magnet induction at saturation
B_M Magnet induction
μo Air permeability
nI Number of ampere turns

<figure III-8>



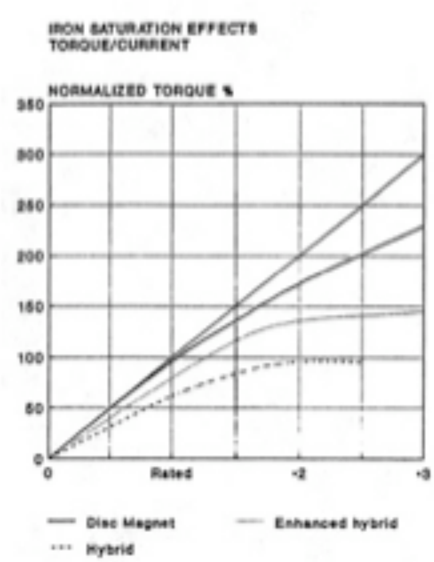
<”Losses in Watt” Table>

Next, observe that the magnetic and electromagnetic circuits are both optimally designed by having the energy source at the airgap. Most motors, which use iron to guide flux, have iron “teeth”. It is the teeth that face the air gap and they are the flux source. The coil(s),is somewhere behind the air gap. Similarly, the permanent magnet poles of the DM motor face the airgaps, they are not buried in the structure, and they do not require any iron pole pieces to direct flux.



<figure III-11>

Recommended and non-recommended circuits are shown in figure III-11 in schematic pictures. What is the penalty of the non-recommended circuit? Losses, lower efficiency and flux leakage. The reason for this is because the airgap is the largest reluctance of any magnetic circuit. When flux is forced to cross an airgap, it will look for all alternative paths. If the flux is led to the airgap in iron it will spew out in the face in all directions. If the permanent magnet is at the airgap the flux will be forced across the gap in a very much more concentrated bundle. The same is true for the electromagnetic circuit in that with the coils “at the airgap” the flux is prevented from wandering.



<”Iron Saturation Effects, Torque/Current” Table>

This feature has many benefits. First, the torque constant is uniform. Many control and/or positioning schemes rely upon this linearity for their success, for instance microstepping and closed loop operation.

With linearity extending beyond rated current the DM motor may be effectively pulsed, or boosted, to get extra torque during the acceleration phase.Typically,100% overcurrent will produce 175% of rated torque. Linearity also produces better positioning accuracy for two-phase operation.

No harmonic distortions

The torque-displacement curves of step motors are supposed to be sinusoids. Any textbook, handbook, manufacturer literature will show such sinusoidal curves. In fact, the curves of all but the DM motor have harmonic distortions due primarily to tooth geometry ratios. To further complicate the matter, the distortion curves are not "constant". That is, as more current is applied the distortion changes and therefore the distortion may not be characterized. DM motor curves are undistorted. Pure sinusoids mean better accuracy when positioning in the microstepping mode of operation where sine cosine current ratios are used. As positioning current varies from zero to maximum, linearity is needed to achieve a consistent torque constant.

These rare earth permanent magnets are utilized in Portescap disc magnet stepper motors so that the motors have all the advantages required for fast incremental motion such as acceleration and power-rate. Electronic improvements also give new opportunities as we always have to consider the entire system and not the motor only.

A few years ago the majority of stepper applications used L/R Unipolar drives. Nowadays more and more applications require current source drives (PWM).The next step towards a system having better performances would be the combination of stepper and BLDC mode; at low speed the stepper would work in microstepping mode and at high speed in BLDC mode.

Technologies are changing and design engineers have to be aware of these new possibilities.

SIDEBAR

Overlapping capabilities

Because of recent changes in cost, torque, setup, and tuning, the line that separates the choice between steppers and servomotors is hazier than ever. Design situations may be further complicated by the fact that a machine often needs both types of motors, depending on the type of axes involved.

Power is usually the first factor considered when making the decision. Usually, below 1000 RPM, the choice falls to steppers, and above 3000 RPM, the choice leans more toward servomotors. But that's changing, especially in the 1000-RPM range, where both types of motors have overlapping capabilities. And considering horsepower, servomotors in the fractional to 2-hp range have the largest overlap with brushed and brushless steppers. Above 2 hp, the brushless servomotor is more typically favored. Because of steppers' increased torque, these motors can provide extremely accurate, stiff performance at low speeds without a gearbox or other type of mechanical advantage.

The disc magnet step motor offers a marriage of the permanent magnet motor with the brushless motor. As a result, designers have the advantage to utilize the low inertia to achieve high torque output at higher speeds. Speeds of up to 10,000 RPM can be achieved with significantly less torque fall-off than a hybrid step motor. This combination is well suited for applications that require quick movement and accurate positioning.

Servomotors are ideally designed to run at high speeds. They can run under precision control at extremely low speeds, even down to 0 RPM. However, because of the oversized rotors now used in steppers, these motors can produce more torque for a given frame size than a servomotor at speeds below 1000 RPM, during stall, or when holding a load. As speeds increase above 1000 RPM, however, the torque within a step motor begins to fall off, whereas in a servomotor, the torque doesn't start to fall off until speed reaches 2500 to 3000 RPM or sometimes higher.

Even with the developments in servomotors that broaden their application range, steppers are still around 30% less costly compared with an equivalent servo system; that percentage used to be higher. Conversely, steppers can be used in applications that have traditionally been servomotor territory. If an application has predictable loads, for example, a stepper can move them with high repeatability and reliability. If external forces are low, a stepper can save cost over a comparable servo system. High-resolution applications are naturals for steppers, whether the motor runs open-loop or has a built-in feedback device. And constant power applications can be more cost effective with steppers rather than servomotors.