Magnetic Design and Applications Using Halbach Theory

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Permanent magnets (PMs) are used in many applications including hybrid electric vehicles, motors, generators, and most consumer electronic devices. With growing demands for rare earth elements, which are essential to rare earth magnets, combined with ongoing environmental concerns and China’s control on rare earth exports in recent years, fears of a global rare earth shortage have emerged. This concern has prompted engineers to come up with designs that do not use rare earth magnets. In April 2012, Hitachi developed an 11 kW PM motor without rare earth materials\cite{1}. It is essential to understand the critical factors and application environment when designing magnetic circuits for satisfactory performance of the device. This is an important step in the design process, which determines the appropriate magnetic parameters used for analytical and/or numerical analysis. In this article Halbach theory and its applications are introduced. PM Halbach arrays are very useful for a variety of applications, including high field magnet sources, magnetizing and de-magnetizing systems, and high power/efficient motors and generators\cite{2}\cite{3}. A Halbach progressive magnetization design can maximize the coupling torque, while a double Halbach cylinder provides an adjustable magnetic field.

**Principle of Klaus Halbach Theory**

Klaus Halbach (1924-2000), a staff physicist with the Lawrence Berkeley National Laboratory, investigated novel designs for PM arrays, using advanced analytical and innovative approaches. In 1979, he published a paper entitled ‘Design of Permanent Multipole Magnets with Oriented Rare Earth Cobalt Material\cite{4}'. In this paper, he introduced a novel method of generating multipole magnetic fields using innovative geometrical arrangements of PMs. Fig. 1 shows an example of linear and circular Halbach arrays.

![Figure 1: Linear (left) and Circular (right) Halbach Array](image)

According to the Halbach theory, if the magnetization of an infinite line source oriented perpendicular to its axis is rotated about that axis, the field it produces remains everywhere constant in magnitude and is everywhere rotated by the same angle in the opposite sense. For an infinite dipole, the tangential and radial field components are:

\[ H_\theta = \frac{\lambda \sin \theta}{2 \pi r^2} \]  
\[ H_r = \frac{\lambda \cos \theta}{2 \pi r^2} \]

where \( \lambda \) is the moment per unit length, and \( \theta \) is the angle measured from the dipolar axis in polar
coordinates. Therefore the magnitude of $H$ is:

$$|H| = (H_\theta^2 + H_r^2)^{1/2} = \frac{\lambda}{2\pi r^2}$$  \hspace{1cm} (3)

$|H|$ is independent of dipolar orientation. The field orientation angle $\alpha$ with respect to the axis is twice $\theta$. A Halbach ring assembly with progressive magnetization can be realized by discrete magnet segments. The direction of magnetization in each individual magnet segment can be expressed by the following relation:

$$\theta_m = (1 \pm p)\theta_i$$  \hspace{1cm} (4)

where $\theta_i$ is the angle between $\theta = 0$ and the center of the $i^{th}$ magnet segment, $p$ is the number of pole-pairs, “+” is for an internal field cylinder, and “-” is for an external field cylinder.

**Single Halbach Cylinder**

The design of a Halbach cylinder is relatively simple. According to Eq. (3), all segments have contributions to a uniform field across the airgap in the vertical direction. The flux density in the airgap of a Halbach cylinder is

$$B = B_r \ln\left(\frac{r_2}{r_1}\right)$$  \hspace{1cm} (5)

where $r_1$ and $r_2$ are the inner and outer radii. Halbach theory enables PMs to be fully competitive with electromagnets for fields up to 2T, and fields as high as 5T can be produced\[^5\]. Eq. (5) suggests there is no upper limit for the field of Halbach cylinders, but practically it is limited by the physical dimensions and the demagnetizing effect for permanent magnets.

Single Halbach principle has been used extensively in a variety of applications, especially for PM brushless machines because of sinusoidal air-gap field distribution, electromotive force waveform, and negligible cogging torque\[^6\]. Due to the self-shielding of the Halbach progressive magnetization, back iron is not essential; therefore the mass and the inertia can be reduced. This will improve the dynamic performance. In addition, magnets can have a significantly high working point compared to conventional designs. This improves the effective utilization of the magnet material and increases the coupling torque. The optimum number of poles is related to the geometry and the airgap, which can be determined by finite element analysis (FEA) as shown in Fig. 2.
Double Halbach Cylinder

A double Halbach cylinder provides an adjustable magnetic field, which consists of two concentric cylinders and each cylinder has the same number of magnet segments. The field in the bore is the vector sum of the two individual fields and its magnitude can be expressed as

\[ B = 2\cos(\alpha) B_r \ln(r_2/r_1) \] (5)

when \( \alpha \) is a rotating angle. If the magnetic orientation of each cylinder is aligned in the same direction \( (\alpha=0^\circ) \), the magnetic field in the center reaches the peak, as shown in Fig. 3. If the magnetic orientation of each cylinder is aligned in the opposite direction, the magnetic field in the center reaches near zero. Torque between the cylinders as they rotate is an important consideration when implementing this design. A double Halbach cylinder is applicable to motors, synchronous machines, magnetic bearings, accelerators, spectrometers, and magnetic refrigeration.

Motor/Generator Application

The design of a motor/generator using a Halbach array is simple and intuitive. Since there is no
back iron used in the design, there are two major advantages and other benefits related to weight and power efficiency. First, the conventional core loss and eddy current loss in the laminations or back iron doesn’t exist in Halbach rotating machines. Secondly, the machine is inherently lightweight because of no back iron, which improves the power density. Furthermore, since the field is uniform, the machine design is not constrained by the air gap. And finally, whirl instability doesn’t exist. In other words, the drag torque of conventional machines is a function of the gap spacing while the torque of a Halbach system is not a function of displacement of the windings relative to the field because of the uniform field. There is a potential disadvantage of Halbach rotating systems: winding losses due to eddy currents in the conductors. This happens because the field is always present and eddy currents will be induced with rotations. These losses can be minimized by the number of windings, but there is a trade-off between the efficiency and the winding size [7].

Radial flux PM (RFPM) and axial flux PM (AFPM) rotating machines are two common types available on the market. In RFPM machines, the magnetic field travels in a radial direction across the airgap between the rotor and stator. In AFPM machines, the magnetic field travels in the axial direction. A RFPM configuration is beneficial for high speed operations, however, there are inherent limits to conventional RFPM machines: poor heat removal from the stator winding to the stator core due to the frame and bottle-neck feature. These limitations can be removed by a new topology of AFPM. AFPM machines have better ventilation and cooling, higher power density, and are more compact in size. A Halbach array can be applied to both RFPM and AFPM machines. Fig. 4 is an example of a 100 kW AFPM generator built at Electron Energy Corporation.

Figure 4: Axial Flux PM Generator Conceptual Design and Prototype

Magnetic Coupler Application

Coupling systems can be found in many applications including chemical, biological, pharmaceutical, and other industrial systems. Magnetic couplings are used to transmit rotational and/or linear motion without direct contact. Magnetic couplers in a mixer, for example, could eliminate the need for seals, which would improve the reliability and safety aspects of such machines, because seals are prone to deterioration over time, causing leaks.

There are rotary couplers, face to face couplers, and linear couplers. Fig. 5 shows an example of
co-axial magnetic coupler with a Halbach array. The torque of magnetic couplers is related to the magnetic properties of permanent magnets, magnet dimensions, the number of poles and the air gap between the driver and driven components. Just like a motor or a generator design, the number of magnet poles will have a significant impact on the torque. An optimum number of poles would help maximize the torque, assuming all other design parameters are the same.

Figure 5: Halbach Magnetic Coupler Concept and Magnetic Design

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