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Novel Halbach Permanent Magnet Solenoid Design using Finite Element Method

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Abstract

To generate the high axial field usually Electromagnetic Coils solenoid is used but it consumes large DC power supplies and cooling system and is not compact. The PM (Permanent Magnet) solenoid on the contrary can give fixed axial field profiles that are very compact and do not require any energy source as they are themselves energy sources. PM solenoids are usually designed using large radial and axial magnetized magnets. The drawback of such a design is using large radial magnets which are often unavailable with assembly problems. The paper discusses the novel Halbach solenoid configuration design and uses ref[1] solenoid results to verify it. The finite element magneto static method is used to analyze the two models. The FEM magneto static analysis was done in Magnet Infolytica FEM magneto static analysis package.

Keywords: FEM, Halbach. PM, Magnetization, Remnant Field, Solenoid

1. Introduction

To generate an intense axial field usually electromagnetic coils solenoid is used. The drawback of Electromagnetic Coil solenoids is that they require large DC power supplies and cooling arrangements. They also occupy large space which makes them not good for certain EM applications.

The Permanent magnet solenoids provide a fixed-designed axial field profile and are compact. They do not require any external power source and cooling.

The Permanent magnet Solenoid is usually made by arranging radially magnetized ring magnets and axial magnetized ring magnets.

The drawback of radially magnetized ring magnets is that such magnets are difficult to manufacture because of the difficulty in guiding sufficient field in the center bore to radially align and magnetized high Coercivity materials.

The solution to the above drawback is to use instead of radial magnetized magnets, used of varied angled magnetized directions magnets. This may pump more fields in the bore but then it will affect on field uniformity.

The drawback of axial magnetized rings is that although they are easy to manufacture but they result in a lower field in the bore with an increased leakage field.

The use of an iron shield to reduce leakage made by axial magnetized rings will further reduce the bore field.

Considering the advantages and disadvantages of radial magnetized rings and axial magnetized rings a mixed configuration is used so the so-called Halbach solenoid configuration Fig1 where axial and radial magnetized rings are arranged alternatively with angular shift of magnetization of 180^0.

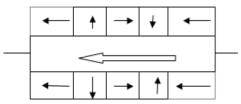

Figure 1. shows a typical Halbach Permanent magnet solenoid configuration with an arrow representing field direction.

The paper[1] Halbach solenoid gives wide aperture Halbach solenoid. However, in this paper an attempt to design a new configuration Halbach solenoid where no azimuthally magnetized radial magnets are used. In this

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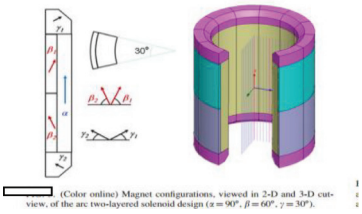
paper, the results of permanent magnet solenoid Halbach given in ref[1] is used for validation of the proposed design. The Novel Solenoid Configuration using a segmented model is very easy to fabricate and also has a sufficient high peak field with negligible negative field. The configuration can be extended to any bore, any length solenoid of the desired center field. The configuration uses axial magnetized structures only. The novel configuration used easily available axial magnets with no soft iron. The paper presents FEM results of paper-based Halbach solenoid configuration[1] and novel Halbach solenoid with detailed analysis and design of novel Halbach solenoid.

2. Round Solenoid Halbach Configuration[1]



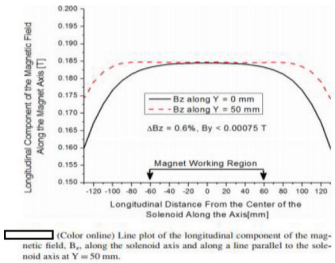
(Color online) Magnet configurations, viewed in 2-D and 3-D cut-view, of the arc two-layered solenoid design ($\alpha = 90°$, $\beta = 60°$, $\gamma = 30°$).

Figure 2. Round Halbach configuration ref[1].

Table 1. Specification of Halbach Solenoid ref[1]

S. No.	Title	Description
1	Dimension	Inter diameter bore 270mmϕ, solenoid Length 470mm
2	Good field region	Axial length±60mm radial length±50mm
3	Field uniformity	0.6% in centre of solenoid with maximum field variation in good field region volume is 11.5%.
4	Maximum axial field	1.8kG

The magnetic field plot for as per ref[1]



(Color online) Line plot of the longitudinal component of the magnetic field, B_z, along the solenoid axis and along a line parallel to the solenoid axis at Y = 50 mm.

Figure 3. Centre axial magnetic field plot of axial round Solenoid[1].

3. Novel Rectangular Axial Magnet-Based Halbach Solenoid Model

The model uses a rectangular bore. This allows the magnet to be used as small rectangular axial magnets with magnetization direction along thickness which are easily available. The rectangular bore is calculated as an equivalent square bore which circumscribes the circular bore of any circular PM solenoid.

Advantages of this novel configuration Halbach solenoid model

- Negligible or zero end fields.
- A Very High center field with high uniformity and length of GFR can be regulated by simply adjusting the length of center axial magnets.
- Easy to fabricate with available axial magnets. No big radial or axial magnet sizes needed.
- No soft iron is used for the focusing field.

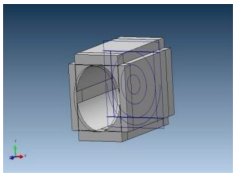


Figure 4. Novel rectangular Halbach permanent solenoid configuration 3D FEM Model.

Table 2. Specification of Novel Halbach Solenoid

S. No.	Title	Description
1	Dimension	Outer Dimension=372×372×478mm Inner Dimension=270×270×478mm
2	Good field region	Axial length±60mm radial length(±50mm)
3	Field uniformity desired	Better then 0.6%in centre of solenoid with maximum field variation in good field region is 11.5%
4	Maximum axial field peak value	1.8kG or better

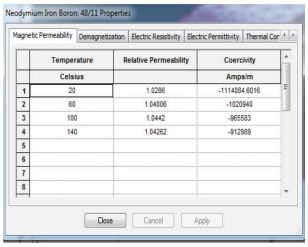


Figure 5. Magnetic property of NDFEB magnet used in FEM magneto static analyses of Novel Halbach Solenoid.

4. FEM Magneto Static Analysis of Rectangular Novel Halbach Solenoid Configuration

The equivalent dimensions are used in the design as per Table 2 above.

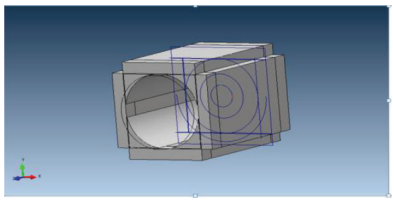


Figure 6. 3D FEM solid model.

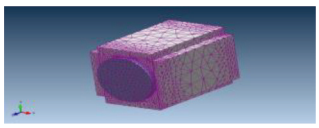


Figure 7. Mesh density= 20mm.

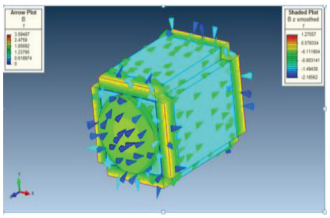


Figure 8. Field plot.

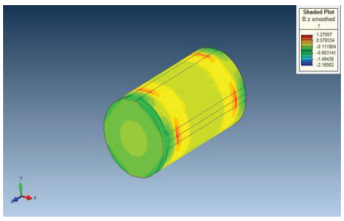


Figure 9. Field plot in 127 mm diameter bore 425 mm length solenoid.

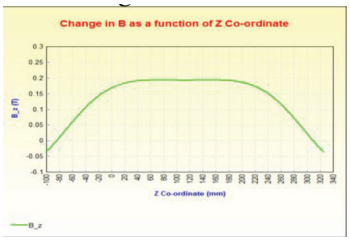


Figure 10. Field plot in center of the solenoid for axial length 425 mm.

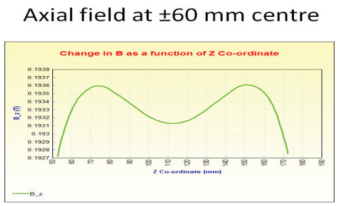


Figure 11. Field plot in centre of the solenoid for axial length 120 mm good field region.

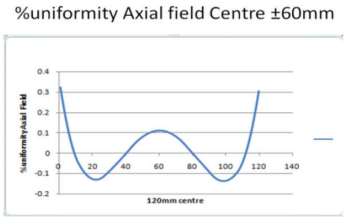


Figure 12. %uniformity field plot in center of the solenoid for axial length 120 mm good field region.

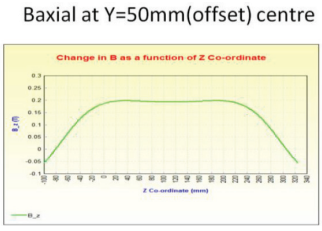


Figure 13. Field plot in center of solenoid for Axial length 425 mm at Y=50 mm offset center.

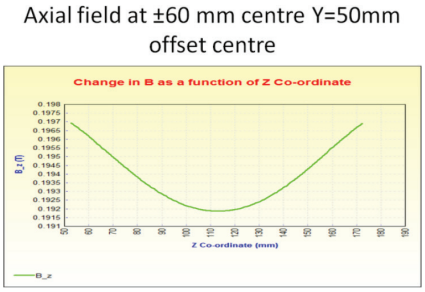


Figure 14. Field plot in center of solenoid for axial length 120mm good field region at Y=50 mm offset center.

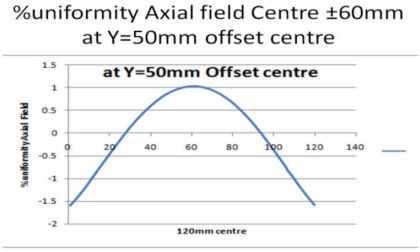


Figure 15. %uniformity field plot in center of the solenoid for axial length 120 mm Good field region at y=50 mm offset center.

Salient Features of Novel Halbach Solenoid Design:

- The axial field at center 0.19T with uniformity 0.3% in ±60mm.
- Field is uniform in GFR of Axial ±60mm and offset center Y = ±50mm.
- Maximum variation of %uniformity from center to offset 50mm from center is 1.5%.
- The PM solenoid field uniformity and Peak field are adjustable to the requirement.
- All magnetic structures used are axial magnets that are easily available or can be made by small axial magnet parts.

5. Features of Halbach Solenoid in Paper and Novel Halbach Solenoid

Table 3. Features of paper based Halbach solenoid ref[1] and Novel Halbach solenoid

S. No.	Parameter	Paper based solenoid[1]	Novel Halbach solenoid
1	Dimension	Outer dimension 372mm OD,270mm ID,470mm length	Outer Dimension-372x372x478mm Inner Dimension 270x270x478mm
2	Magnetization direction	Complex angle of magnetization esp. radial magnets a challenge	Simple axial magnetized structures which are easily available in market.
3	Maximum field	0.18T	0.19T
4	Axial field uniformity in 160mm,±50mm centre	0.6%[1]	0.3%
5	Axial field uniformity in 160mm,±50mm radial	11.5% as[1]	<1.5%
6	Ease of fabrication	It needs radial magnets so have fabrication difficulties	It uses only axial magnetized structures so comparable easy to fabricate.

Advantages of Novel Halbach solenoid configuration

- Negligible or zero-end field.
- Very high uniformity and high field values.
- Uses readily available axial magnetized magnet.
- Easy to fabricate.
- The model can be extended for any bore in any field easily.

6. Conclusion

The Novel Halbach solenoid configuration gives a high solenoid stable field with high uniformity. It can be easily fabricated since it uses an axially magnetized magnet. It can be made in segments and modular. It results in zero or negligible end negative field.

7. Acknowledgment

The author would like to thank Head, EmA, and ID for all providing encouragement and support during the scope of work.

8. References

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