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A Feasibility Study to Apply the Bitter Magnet to Electric Power Devices

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Abstract -The ``Bitter'' magnet has been serving high field science community over decades, since its first implementation by MIT in the 1930s and its variation of the Florida Bitter by the National High Magnetic Field Laboratory in the 1990s. With a proper water-cooling environment, average current density of such a bitter magnet reaches ~600 $\mathrm{A/mm^2}$ with a field generation capacity of >40 T. This paper reports our initial efforts to apply the Bitter magnet to electric power applications with focus on water cooled axial-flux type synchronous motor. Due to the high-energy-density feature of the Bitter magnet, the new power machines may be substantially more compact than the conventional counterparts. Also, owing to the rigid structure of the Bitter windings, we expect lower vibration noise in operation of such machines. In spite of these benefits, mainly due to the requirement of high pressure coolant, the overall system's efficiency must be carefully examined. As the first step of our research, this paper reports: (1) key concept of the Bitter magnet electric machine; (2) electromagnetical and thermal considerations; and (3) preliminary design of selected machines.

◆ Introduction : A Study to Apply Bitter Magnet to Electric Machine

- Bitter plate magnet consists of a stack of copper plates and insulators with many cooling holes which makes it can have high current density.
- To applying it to multipole machine, several kinds of Bitter magnet shape were proposed, and a pizza plate type magnet case was studied in this paper.
- Electromagnetic and mechanical design were performed to apply to axial-flux synchronous machine.

◆ Bitter Plate Magnet : Extremely High Energy Density of Resistive Magnet with External Cooling

- The Bitter plate magnet (Fig. 1) was invented by Francis Bitter in 1933 to generate strong magnetic field.
- The magnet can have much higher current density ($> 100\ \mathrm{A/mm^2}$) with proper external cooling
- It can be an alternative of permanent magnet due to its extremely high energy density.
- To apply the magnet to multipole electric machines, its shape should be changed.
- In this paper, analyses were performed using pizza plate type Bitter magnet (Fig. 2).
- Some other proposed shapes of Bitter plate magnet are shown in Fig. 3

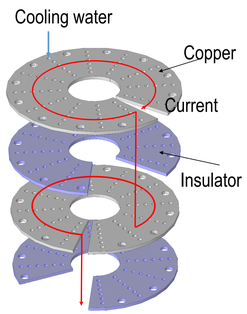

Figure 1. Configuration of Bitter plate magnet

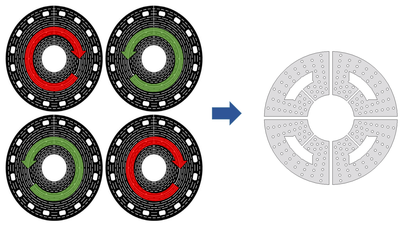

Figure 2. Pizza plate type Bitter magnet for multipole machine

Figure 3. Other proposed shapes of Bitter plate magnet for multipole machine

- The skew structure of Bitter plate magnet not only improves the performance of the machine, but also contributes to more effective heat transfer.

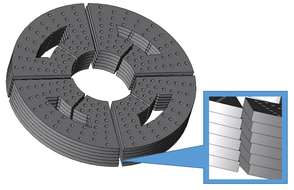

Figure 4. Skew structure of 4 pole pizza plate type Bitter magnet

◆ Electromagnetic Design : Bitter Magnet Synchronous Machine

- Rotor and stator coils can be replaced by Bitter magnet.
- The Bitter magnet can be an alternative of permanent magnet.
- Both air-core and ferrite core can be considered depending on application.
- Figure 5. shows a case of Bitter magnet used as field coil.

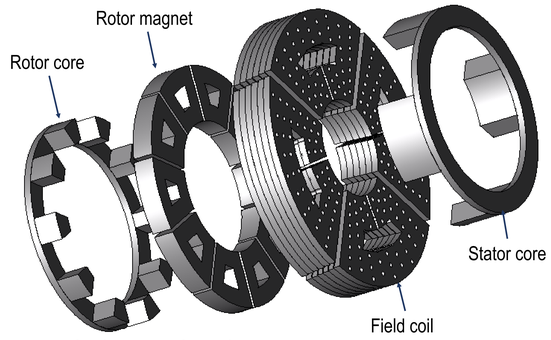

Figure 5. Configuration of axial flux Bitter plate magnet machine

- In this paper, all of rotor and stator coils were replaced, and its current density was assumed $100\ \mathrm{A/mm^2}$.
- Air-core was used, and other magnetic material structure of machines were not considered.
- The machine was represented using Quasi-3D IRMA[1] model and it was analyzed using Finite Element Method (FEM)

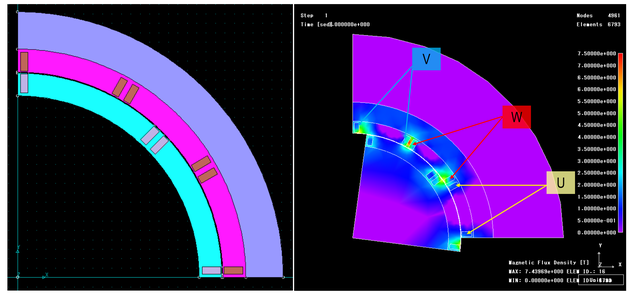

Figure 6. (a) Quasi-3D IRMA model of air core axial-flux Bitter plate magnet synchronous machine; and (b) its field calculation results

- According to results shown in Table 1, the Bitter magnet machine has much higher torque and energy density because of its higher current and compact structure.
- These machines can be used for large scale applications which need very high torque such as elevator and ship propulsion.

Application	Inner radius (m)	Outer radius (m)	T ($N \cdot m$)
Vehicle	0.06	0.21	227
	0.13	0.43	7.3×10^3
Elevator, ship propulsion	0.19	0.64	55×10^3
	0.25	0.85	229×10^3
	0.32	1.07	675×10^3

Table 1. Conceptual electromagnetic design results

◆ Thermal Design : Design for Effective Cooling

- Wavy cooling path improves heat transfer by generating vortexes in water flow, and it can be obtained using skewing structure.
- The example of cooling path can be shown in Fig 3,
- With these wavy path cases, the temperature of the magnet can be maintained using relatively low cooling power.

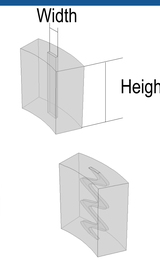

Figure 6. Straight cooling path case (up); and wavy path cases (down)

- Cooling hall shape design is also necessary to reduce current concentration in copper plate.
- Elliptical holes can make the current more uniform.
- The elliptical sides of hall can also reduce mechanical stress[2]

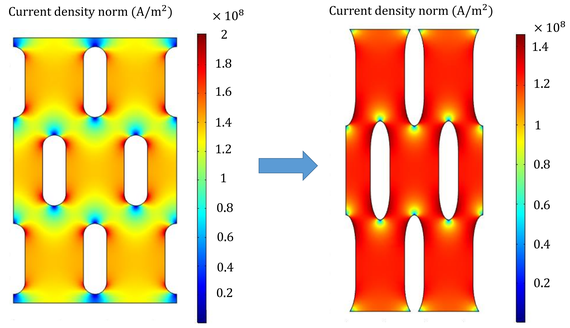

Figure 7. Current distribution change in copper plate depending on hall shape

◆ Discussion and Conclusion

- The Bitter magnet can have much higher current density with external cooling, and it can be an alternative of permanent magnet due to its extremely high energy density.
- To apply this magnet to electric power devices, axail-flux synchronous motor was selected as a case study.
- The motor can have much higher air-gap flux density and torque.
- To maintain machine temperature in a proper level, thermal analyses were performed especially for cooling path and hole shape.
- But, due to its high current density, future work to improve its efficiency is required.

References
[1] M. Gulec *et al.*, "Implementation of different 2d finite element modelling approaches in axial flux permanent magnet disc machines," IET Electric Power Applications, vol. 12, no. 2, pp. 195–202, 2017.
[2] M. D. Bird *et al.*, "Design of the next generation of florida-bitter magnets at the nhmfl," IEEE Transactions on Applied Superconductivity, vol. 14, no. 2, pp. 1253–1256, June 2004.