The Effect of Different Types of Rare Earth Magnets on the Torque of Spoke-Type Permanent Magnet Vernier Motor

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***Abstract*— The Vernier motor family is a type of electric motor that provides high torque density at low speed. In this paper, the spoke-type permanent magnet Vernier motor, which is a new type of permanent magnet Vernier motor, is discussed, and the concept of rare earth magnets is also discussed. To check the output torque of spoke-type permanent magnet Vernier motors, different rare earth magnets have been placed and the output torque value has been calculated for each and compared with ordinary magnets which are more economical and cheaper. In this comparison, it is concluded that using a certain type of magnet has the best results in the output torque, and using a magnet is more economical.**

***Index Terms*— Spoke-type permanent magnet Vernier motor, Finite element method, Rare earth magnet, Average torque.**

I. INTRODUCTION

The initial Vernier machines and Vernier theory were proposed in 1957 [1]. There are different types of Vernier machines, which can be mentioned as linear [2], non-linear, and permanent magnet Vernier machines. The design of permanent magnet machines is a very important issue in the industry [3], and permanent magnet Vernier machines are a new type of them. Permanent magnet Vernier machines feature great torque and efficiency because the magnet on the rotor creates a higher torque density[4]. Permanent magnet Vernier machines are known for their high torque density [5]. In permanent magnet Vernier machines, the number of rotor and stator poles are different from each other [6].

Permanent magnet Vernier machines are structurally similar to permanent magnet synchronous machines and are in the category of constant-speed machines. Permanent magnet Vernier motors have a complex torque generation mechanism that uses a hidden virtual magnetic gearbox in their air gap to modulate the magnetic flux and generate torque. Therefore, to better understand the concept of torque generation in Vernier motors, it is necessary to learn the torque generation mechanism in magnetic gearboxes.

The number of rotor poles in permanent magnet Vernier motors is determined by the magnet pair on the rotor. There are two locations for magnets in these motors. Magnets are positioned on the rotor's surface in the first kind and drilled inside the rotor in the second type [7]. Permanent magnet Vernier machines are made in different types that have different applications in the industry, which can be mentioned as two-rotor and two-stator types. In some permanent magnet Vernier motors, flux barriers are used behind the magnet on the rotor, which are called flux barrier permanent magnet Vernier motors [8].

Nowadays, permanent magnet Vernier motors have many applications in the industry. Torque is one of the important parameters of Vernier machines. The placement of magnets in Vernier machines can help improve torque. The location of the magnet and the direction of the magnet arrays and the type of rotor are effective in the average torque value [9].

In this research on the magnets used on the rotor, the most powerful type of magnet and also the most economical type of magnet on the motor have been tested. Then, a stronger alloy than NdFeB a magnet has been used, the relative permeability of which is higher than the normal type of this magnet, and it has been compared with other rare earth magnets. The main purpose of this article is to compare the torque output of Vernier motors with rare earth magnets with the NdFeB magnet proposed in this article.

II. THE EFFECT OF FLUX BARRIER ON THE FLUX PATH

Fig. 1 shows a view of a spoke-type permanent magnet Vernier motor (SVPM) without a flux barrier and Fig. 2 shows a view of a spoke-type permanent magnet Vernier motor with flux barriers.

In permanent magnet Vernier motors that have flux barriers, the magnetic flux is closed in a specific path, which makes the output torque more optimal and increased. The differences in

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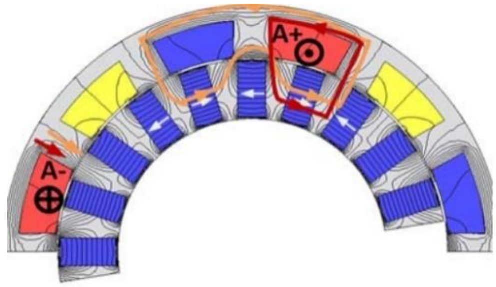

Fig. 1. SVPM without flux barriers [8]

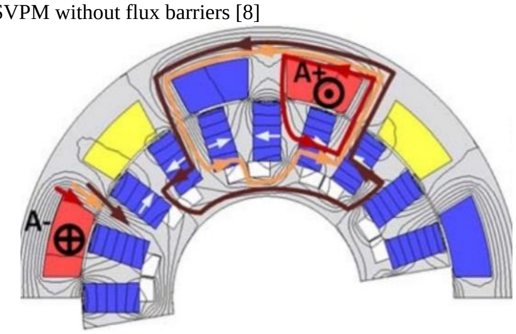

Fig. 2. SVPM with flux barriers [8]

the magnetic flux closing path in Fig. 1 and Fig. 2 can be compared with each other. In SVPM without flux barriers, this path passes over the rotor magnets, but in SVPM with flux barriers, it passes behind the barriers and magnets. This motor's ability to generate high output torque at low speeds is a result of a virtual magnetic gearbox that modifies the magnetic flux.Analysis of Operating Principle

A. Torque Theory in SVPM

In this section, the equations governing the torque generation of SVPM with flux barriers are discussed. In (1) which describes the output torque of SVPM [10].

$$T = \frac{d_{is} l_i}{2} \int_0^{2\pi} (\frac{\partial}{\partial \theta_{rm}} B_{rg}) F_{sg} d\theta_s \quad (1)$$

In (2), the magnetic flux density of the SVPM is calculated [4].

$$B_{rg} = \hat{P}(\theta) B_g(\theta_s) \quad (2)$$

In (3), the equation of the magnetic driving force of the SVPM is obtained [8].

$$F_{sg} = \sum_{h=1,5,7,11} \left(\frac{3}{2\pi}\right) \frac{k_h N_t I_{pk}}{h C_p P_s} \times \cos\left(h \frac{P_s}{2} \theta_s \pm (\omega_e t - \gamma)\right) \quad (3)$$

B. Rare Earth Magnets

These special metals act like super strong magnets, but only when it’s really cold**.** On their own, their magnetic powers disappear at room temperature. However, mixing them with other metals like iron, cobalt, or nickel creates new materials that stay magnetic in the warm room. These super alloys keep the unique direction-sensitivity of the special metals, thanks to their special atomic structure. Think of it like tiny compass needles inside each atom, always pointing in the same direction.

C. Alnico

Certain metal mixtures, called alnicos and recognized by various brand names, combine iron, cobalt, and nickel as major components with smaller amounts of aluminum, copper, and sometimes other elements. The name alnico references the chemical symbols of its key elements (Al, Ni, Co), although iron forms the bulk of every alnico alloy. Despite previously being the preferred material for permanent magnets, alnicos have mostly been replaced by other materials like ferrites and rare-earth alloys. One benefit of alnicos is their high Curie temperature, which means their magnetic properties barely change around room temperature, making them useful in specific situations. Once the go-to magnets for decades, alnicos are iron-based alloys with various names. They mix significant amounts of iron, cobalt, and nickel, with smaller amounts of aluminum and copper. The name "alnico" comes from these key elements, even though iron is the main one. While replaced by other magnets in many uses, alnicos still shine in situations where their high-temperature resistance matters, like some instruments and sensors.

D. SmCo(5)

The hexagonal crystal structure of this compound translates to exceptional magnets via a meticulous production process. The alloy is initially melted and cast, followed by crushing and grinding to generate a micron-sized powder, with each particle containing a single $SmCo_5$ crystal. Subsequently, the powder undergoes magnetic field alignment, guaranteeing parallel 'easy axes' for optimal magnetization. The aligned powder is then compacted and sintered at temperatures exceeding $1000^{\circ}C$ to attain the final magnet. To achieve superior density and magnetic properties, a small quantity of powder enriched with excess Sm is incorporated before compaction. This additional material melts during sintering, playing a crucial role in achieving high density.

E. FeNdB

A new magnetic material was found, which was placed in the category of optimal and powerful permanent magnetic materials. $Fe_{14}Nd_2B$ is a type of tetrahedral crystal that has four sides. The Curie temperature of this new magnetic material is above 300°C. This new magnetic material has the same manufacturing equipment and production process as Sm-Co, and this material can be mass-produced. One of the problems of this magnet is corrosion at high temperatures, which is solved by metal and non-metal shields and covers. In Fig. 3 three comparisons of magnetism are given.

III. FINITE ELEMENT METHOD

In this paper, the two-dimensional finite element method is used to analyze the SVPM. With this method, electric motors can be analyzed in different states such as transient and magnetic [12]-[14]. Ansys Electronics Desktop software is used in this section. In modeling the permanent magnet Vernier motor in this article, transient analysis is used in the software. In this study, the material of the rotor magnets has been

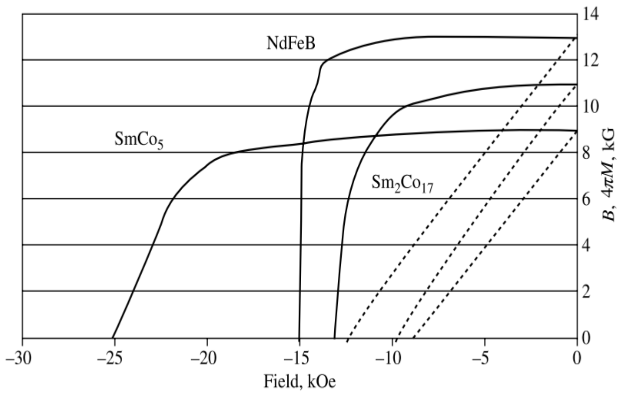

Fig. 3. Characteristics of demagnetization in rare-earth permanent magnets [11]

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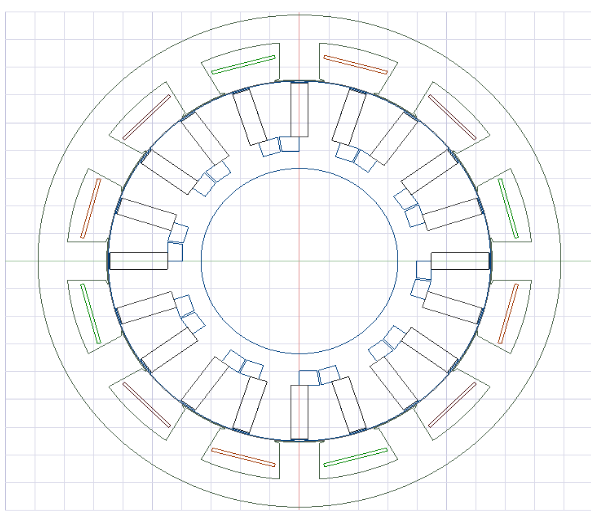

Fig. 4. SVPM model in simulator software

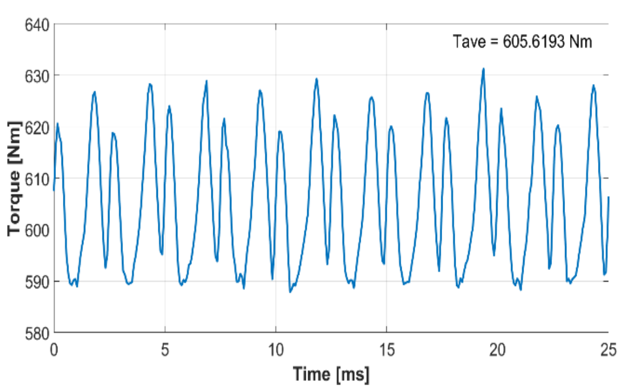

Fig. 5. Diagram of the torque of the SVPM with a $Fe_{14}Nd_2B$ magnet with a residual magnetization of 1.03 T

simulated in this software according to the previous section, and the torque results have been reported.

A. Simulation with $Fe_{14}Nd_2B$

In the first step, the SVPM, which is given in [4], is simulated with a $Fe_{14}Nd_2B$ magnet with a residual magnetization of 1.03 T and a Curie temperature of $300^{\circ}C$. The simulated model of the motor is shown in Fig. 4. Fig. 5 shows the result of the torque simulation of this motor

Another alloy of this type of magnet has a curie temperature of about $400^{\circ}C$ and its residual magnetism is about 1.4 T. This alloy is stronger than the previous alloy and increases the torque, this can be seen in Fig. 6.

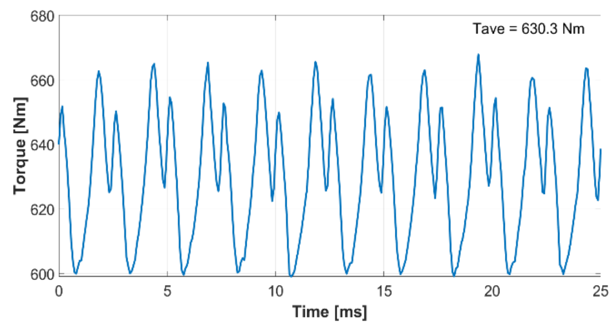

Fig. 6. Diagram of the torque of the SVPM with a $Fe_{14}Nd_2B$ magnet with a residual magnetization of 1.4 T

B. Simulation with $SmCo_5$

In the second step, the SVPM with the $SmCo_5$ magnet is placed on the rotor. The result of the output torque of this motor is shown in Fig. 7.

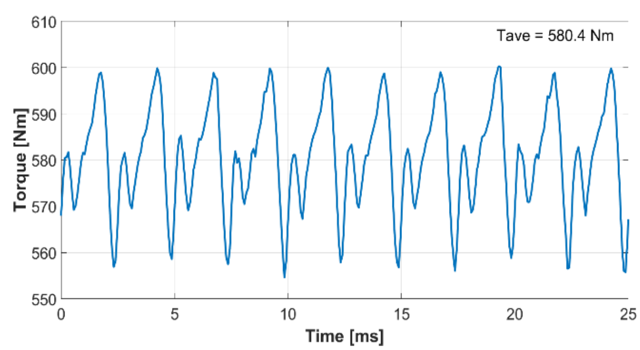

Fig. 7. Diagram of the torque of the SVPM with a $SmCo_5$ magnet

C. Simulation with Alnico

In the third stage, the SVPM is placed on the rotor with an Alnico magnet. This magnet has weaker magnetic power but is relatively cheaper. The result of the output torque of this motor is listed in Fig. 8.

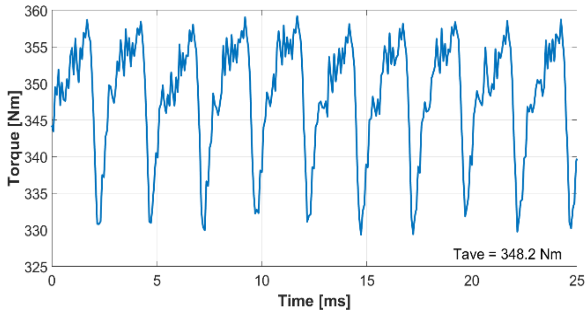

Fig. 8. Diagram of the torque of the SVPM with an Alnico magnet

D. Back-EMF

The back-emf means the rate of change of flux in the no-load state concerning time, which is given in (4) [8]. The back-emf diagram for the SVPM with different types of magnets is shown in Fig. 9.

$$e = \frac{d\lambda}{dt} = \frac{d\lambda}{d\theta_m} \times \frac{d\theta_m}{dt} = \omega_{rm}\frac{d\theta_m}{dt} \tag{4}$$

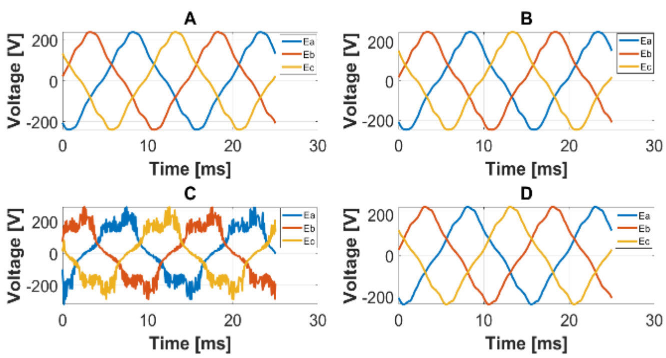

Fig. 9. Back-emf diagram for SVPM (A): for $Nd_2Fe_{14}B$ the magnet with the residual magnetization of 1.03T, (B): for $SmCo_5$ the magnet, (C): for the Alnico magnet, (D): for $Nd_2Fe_{14}B$ the magnet with the residual magnetization of 1.4T

In this article, the average torque produced by different magnets is investigated. The production of torque in permanent magnet Vernier motors depends on the flux density produced by the magnets, and the use of magnets that lead to the production of more flux density can increase and optimize the production of torque. Therefore, the use of magnets that have a higher relative permeability can be useful for doing this task. The simulation results of SVPM with different magnets are summarized in Table I.

TABLE I
Comparison of the Average Output Torque for SVPM with Different Magnets

Magnets	Torque[nm]
$Nd_2Fe_{14}B$ (B_r = 1.03 T)	605.6
$Nd_2Fe_{14}B$ (B_r = 1.4 T)	630.3
Alnico	580.4
$SmCo_5$	348.2

IV. CONCLUSION

The SVPM is covered in this publication. It may be inferred from the simulation analysis that rare earth magnets have a substantially larger motor output torque than other magnet types. However, the production of this kind of motor is quite expensive because to its high cost and rarity in some countries. It is also easier to construct, but the output torque is less when cheaper magnets like Alnico are used. Also, using stronger neodymium magnet alloys can increase the average output torque from 605 Nm to 630 Nm because the torque density will be higher.

NOMENCLATURE

B_{rg}	Airgap flux density
l_i	Stack length
F_{sg}	Stator MMF
d_{is}	Inner stator radius
$\hat{P}(\theta)$	Relative permeance
k_h	h^{th} harmonic winding factor
N_t	Total number of turns
I_{pk}	Stator peak current
P_s	Number of stator poles
θ_s	Spatial angle of the stator MMF
ω_e	Angular speed of the motor
γ	Current phase shift angle
λ	Magnetic flux
θ_{rm}	Mechanical rotor rotation angel
ω_{rm}	Mechanical rotor rotation velocity

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