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**A New Flux-Mnemonic Dual-Magnet Brushless Machine**

Wenlong Li, K. T. Chau, Yu Gong, J. Z. Jiang, and Fuhua Li

Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong

This paper presents a new flux-mnemonic dual-magnet brushless machine which incorporates both the neodymium-iron-boron (NdFeB) and aluminum-nickel-cobalt (AlNiCo) permanent magnets (PMs) for hybrid excitation. By applying a temporary current pulse in a small magnetizing winding to online tune the magnetization of AlNiCo PMs, the proposed machine can provide flexible air-gap flux control, thus achieving high efficiency at different speeds and loads. By newly using a parallelogram to model the AlNiCo PM hysteresis loop and then incorporating into the finite element field equation, the performance of the proposed machine is analyzed. Finally, experimental results are given to verify the simulation, confirming the validity of the proposed machine and its analysis.

*Index Terms—Dual-magnet, flux-mnemonic, hybrid excitation, memory machine.*

I. INTRODUCTION

Permanent Magnet (PM) machines, which exhibit high power density and high efficiency, are used widely in industry, especially for electric vehicle propulsion and wind power generation [1]–[3]. However, due to the constant flux produced by PMs, the PM machines can not easily provide air-gap flux control. Recently, the hybrid PM machine [4], [5] and the flux-mnemonic PM machine (also called the memory machine) [6], [7] have been proposed to online control the air-gap flux. The hybrid PM machine utilizes both PMs and DC field windings for hybrid excitation, in which the DC field current is controlled to adjust the air-gap flux. However, since the DC field winding needs a continuous DC current for excitation, it inevitably involves additional copper loss which degrades the overall efficiency and power density. On the other hand, the flux-mnemonic PM machine, which employs the aluminum-nickel-cobalt (AlNiCo) PM, can achieve the controllable air-gap flux by applying a temporary current pulse to the magnetizing winding to online tune the magnetization level of AlNiCo PMs. However, the AlNiCo PM exhibits a low coercivity, which is prone to accidental demagnetization and thus limiting the machine power rating.

The purpose of this paper is to propose and implement a new flux-mnemonic dual-magnet brushless machine which incorporates both the neodymium-iron-boron (NdFeB) and AlNiCo PMs to provide hybrid excitation, thus not only retaining the feature of online tunable air-gap flux control but also improving the machine power density.

II. MACHINE DESIGN

Fig. 1 depicts the topology of the proposed flux-mnemonic dual-magnet brushless machine, which adopts an outer-rotor inner-stator structure. The PMs, magnetizing windings and 5-phase armature windings are all in the inner stator. The outer rotor only consists of laminated iron, which is convenient for application to direct-drive wind turbines [7] and electric vehicle in-wheel motors. The two kinds of PMs, namely the NdFeB and AlNiCo, are located beneath the armature windings and magnetized in radial direction. Each PM pole is constituted by 3 PM segments, two thin NdFeB PM segments and one thick AlNiCo PM segment, which are in shunt nature. The armature windings are fed by 5-phase rectangular currents to produce the desired torque, while the magnetizing windings are fed by positive or negative current pulses to tune the magnetization level of AlNiCo PMs and hence to adjust the air-gap flux.

The concept of controllable air-gap flux lies on the tunable operating point of AlNiCo PMs. The $B - H$ characteristics of the AlNiCo and NdFeB PMs are depicted in Fig. 2. For the AlNiCo PM, when there is no external magnetomotive force (MMF), the operating point is $P$. In order to lower the PM magnetization level, a demagnetizing MMF $F_{\text{demag}}$ is applied so that the operating point shifts from $P$ to $Q$. After removing this demagnetizing MMF, it moves along the recoil line $QR$ to $R$. Thus, the magnetization level is reduced and memorized. Similarly, the operating point can shift back to $P$ when a proper magnetizing MMF is applied. On the contrary, because of its linear demagnetization characteristic, the NdFeB PM does not possess this elegant feature. As the demagnetizing MMF is removed, the operating point retrieves from $N$ to $M$.

The key design data of the proposed machine are listed in Table I. The NdFeB PM provides the main air-gap flux while the AlNiCo PM serves for flux regulation which can be outward-magnetized (OM) to strengthen the air-gap flux or inward-magnetized (IM) to weaken the air-gap flux. By calculating the air-gap flux ratio under the situations of fully OM and fully IM...
of the AlNiCo PM, the flux control range of the proposed machine can be deduced. Fig. 3 shows the equivalent magnetic circuits of these two situations where \( F_{m+} \) and \( F_{m-} \) are the temporary magnetizing winding MMFs to create the OM and IM magnetization of the AlNiCo PM, respectively. After magnetization, \( F_{m+} \) and \( F_{m-} \) become zero so that the relationship of the corresponding air-gap fluxes \( \Phi_{b+} \) and \( \Phi_{b-} \) can be obtained as:

\[
\Phi_{b+} = \frac{F_{PN}R_{PA} + F_{PA} + F_{PN}}{F_{PN}R_{PA} - F_{PA} - F_{PN}}, \quad \Phi_{b-} = 0
\]

For a given control range of air-gap flux, the machine dimensions and parameters can be initially determined by (1).

### III. Analysis Method

To analyze the proposed machine, the domain of interest is one pole-pair which involves 2 pieces of AlNiCo PMs and 4 pieces of NdFeB PMs. A parallelogram hysteresis (PH) model of the AlNiCo PM is coupled with the time stepping finite element method (TS-FEM). Thus, after each magnetization or demagnetization of the AlNiCo PM, its new remanence is updated by the PH model and then fed into the electromagnetic field equation for field computation.

The field equation of the machine is given by:

\[
\nabla \times (\sigma \nabla \times A) = J + \nabla \times (\mu B) - \frac{\partial A}{\partial t} \tag{2}
\]

where \( A \) is the magnetic vector potential, \( J \) is the current density, \( B \) is the remanence of PMs, \( \sigma \) is the magnetic reluctivity, and \( \mu \) is the electrical conductivity. The three terms on the right hand side of (2) correspond to the current region, the PM region and the eddy current region respectively.

The circuit equation of the machine at motoring is given by:

\[
V_s = \frac{L}{S} \int_{\Omega} \frac{\partial A}{\partial t} d\Omega + R_i + L \frac{d\omega}{dt} \tag{3}
\]

where \( V_s \) is the input voltage, \( R \) is the end resistance, \( L \) is the end inductance, \( I \) is the machine stack length, \( S \) is the cross-section area of each conductor, and \( \Omega \) is the winding area.

The torque equation is given by:

\[
J_m \frac{d\omega}{dt} = T_e - T_l - \lambda \omega \tag{4}
\]

where \( J_m \) is the moment of inertia, \( \omega \) is the machine speed, \( T_e \) is the electromagnetic torque, \( T_l \) is the load torque, and \( \lambda \) is the damping coefficient.

Due to the nonlinear characteristic of the AlNiCo PM, a PH model is developed to determine the operating point of the AlNiCo PM under different magnetization levels. As shown in Fig. 4, the major and minor magnetization loops of the hysteresis curves can be represented by a set of parallel lines. These lines are expressed as three linear equations:

\[
B_1 = \frac{\mu_0 H_m + B_{rl}}{H_m - H_c} (H - H_c) \tag{5}
\]

\[
B_{II} = \mu_0 H_m + B_{rl}, \quad n = 1, 2, 3 \ldots \tag{6}
\]

\[
B_{III} = \frac{\mu_0 H_m + B_{rl}}{H_m - H_c} (H - H_c) \tag{7}
\]

where \( B_1, B_{II}, B_{III} \) are the flux densities in the AlNiCo PM representing the right boundary line, the middle parallel lines and the left boundary line of the parallelogram respectively, \( H \) is the corresponding field intensity, \( \mu_0 \) is the permeability of air, \( \mu_r \) is the recoil permeability of the AlNiCo PM, \( H_c \) is the coercivity of the AlNiCo PM, \( B_{rl} \) is the remanence in the major loop, \( B_{m}(n = 1, 2, 3 \ldots) \) represent different remanence values of the AlNiCo PM under different magnetization levels, and \( H_m \) is defined as shown in Fig. 4.

These three equations correspond to the right boundary line, the set of parallel lines in the middle and the left boundary line respectively. Namely, (5) and (6) are used during the magnetization operation, while (6) and (7) are used during the demagnetization operation.

In the initial magnetization process, the remanence of the AlNiCo PM is set to zero. When a positive current pulse is fed to the magnetizing winding, the field intensity \( H_0 \) in the AlNiCo PM region is calculated by (2) using the TS-FEM. Consequently, the remanence \( B_r \) is determined by:

\[
B_r = \begin{cases} 
0 & 0 < H_m < H_c \ 
\frac{\mu_0 H_m + B_{rl}}{H_m - H_c} (H_0 - H_c) - \mu_0 H_m & H_c < H_m < H_m \ < H_0 \ 
\frac{\mu_0 H_m + B_{rl}}{H_m - H_c} (H_0 - H_c) & H_m < H_0 
\end{cases} \tag{8}
\]
After initial magnetization, the remanence $B_r$ is recorded for the next step. If a negative current pulse is fed to the magnetizing winding for demagnetization, a new field intensity $H$ of each element in the AlNiCo PM region is calculated by (2) with the recorded remanence $B_r$. If $H$ is greater than $-H_n$, the remanence $B_r$ will be kept unchanged; otherwise it will be adjusted according to:

$$B_{rm} = \begin{cases} \frac{\mu_0m(H_0 + H_c) - \mu_0q_H H}{(1 - \lambda)}B_{rm} + \lambda(B_{rm} - B_{rm-1}) & -H_n < H \leq H_c \\ \frac{\mu_0m(H_0 - H_c) - \mu_0q_H H}{(1 - \lambda)}B_{rm} + \lambda(B_{rm} - B_{rm-1}) & H < -H_c \end{cases} \quad (9)$$

where $\lambda \in (0, 1)$ is named the adjustment coefficient. If a new record of $B_{rm}$ is obtained, the above process will be repeated until the condition of $H$ is satisfied. For the magnetization process, each new $B_{rm}$ is adjusted according to:

$$B_{rm} = \begin{cases} \frac{\mu_0m(H_0 + H_c) - \mu_0q_H H}{(1 - \lambda)}B_{rm} + \lambda(B_{rm} - B_{rm-1}) & -H_n < H \leq H_c \\ \frac{\mu_0m(H_0 - H_c) - \mu_0q_H H}{(1 - \lambda)}B_{rm} + \lambda(B_{rm} - B_{rm-1}) & H < -H_c \end{cases} \quad (10)$$

The flowchart of the adjustment algorithm for the AlNiCo PM is depicted in Fig. 5.

### IV. Performance Verification

In order to verify the proposed machine and confirm the validity of the analysis method, both simulation and experimentation have been carried out.

By using the PH model coupled TS-FEM, the magnetic field distributions under the non-magnetized AlNiCo PM ($I_m = 0$ A), the fully OM AlNiCo PM ($I_m = 10$ A) and the fully IM AlNiCo PM are shown in Fig. 6. The corresponding air-gap flux density distributions are shown in Fig. 7. It can be found that the air-gap flux control range is about 8, which agrees well with (1). The case in Fig. 6(c) is useful when the motor purposely operates at the high-speed low-torque constant-power region for electric vehicle level cruising. Under the OM status, the AlNiCo PM has the same magnetic orientation as the NdFeB PM, hence reinforcing the air-gap flux density. On the contrary, under the IM status, the AlNiCo PM has an opposite magnetic orientation as the NdFeB PM. The AlNiCo PM essentially shunts the NdFeB PM, thus significantly weakening the air-gap flux density.

When the proposed machine runs at 300 rpm, the corresponding no-load EMF waveforms under different levels of air-gap flux density resulted from the use of $I_m = 10$ A and $I_m = -4$ A are obtained as shown in Fig. 8. It illustrates that the no-load EMF magnitude can be flexibly controlled over a range of 8 times.

Based on the machine prototype, the no-load EMF waveforms at 300 rpm under the use of $I_m = 10$ A and $I_m = -4$ A are measured as shown in Fig. 9. It can be observed that the measured waveforms closely agree with the simulated waveforms with an error within 5%. It not only confirms the validity of the proposed machine, but also the feasibility of the proposed PH
model of the AlNiCo PM for TS-FEM analysis. As compared with the Preisach model [8], the PH model needs only to compute linear equations and does not need to store huge variables, thus saving a lot of CPU time and memory. Furthermore, Fig. 10 shows the measured no-load EMF waveforms at 100 rpm and 300 rpm without and with the use of flux control. Without flux control, the magnitude of no-load EMF varies with the speed. With flux control, the magnitude can be kept unchanged. Therefore, the proposed machine can achieve wide-range constant power operation for motoring and wide-range constant output voltage for generating, both are particularly attractive for electric vehicle propulsion and wind power generation, respectively.

V. CONCLUSION

In this paper, a new flux-mnemonic dual-magnet brushless machine has been designed, analyzed and implemented. By incorporating both the NdFeB and AlNiCo PMs to provide hybrid excitation, the proposed machine not only retains the feature of online tunable air-gap flux control but also improves the machine power density. Also, by incorporating the PH model of the AlNiCo PM into the TS-FEM, the machine performance has been analyzed and simulated. Finally, experimental results are given to verify the simulation results, hence confirming the validity of the proposed machine and its analysis method. Theoretically, the adjustment of air-gap flux can be continuous. In practice, the resolution is limited by the accuracy of the magnitude of current pulses that can be provided by the power converter for the magnetizing winding.

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