Improved Torque Capacity for Flux Modulated Machines by Injecting DC Currents Into the Armature Windings

Shaofeng Jia, Ronghai Qu, Dawei Li, Jian Li, and Wubin Kong

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China.

Flux modulated machine (FMM) comprises three parts: a conventional stator with armature winding, a rotor with permanent magnet, and iron flux modulation pole. Thanks to the inherent magnetic gearing effect, FMMs have been gaining more attention for their features of high torque density. So far, the windings of existing FMMs are fed with pure sinusoidal current. In this paper, to further improve the torque density using the magnetic gear principle, dc-biased sinusoidal current is innovatively injected into the armature coils which are arranged in a specific way, and the electromagnetic performance is analyzed by the finite element analysis. The results show that the electromagnetic torque contains not only the preexisting PM torque, but also the additional torque produced by the dc current interacted with the ac armature current. What is more, it is found that with the proposed dc-biased current, the torque density is improved under the constant copper loss compared with the existing pure sinusoidal current. Besides, the flux adjustment ability is greatly enhanced since the exciting field can be easily adjusted by the injected dc current.

Index Terms—Concentrated coil winding, dc current injected, dual stator, flux modulated machines (FMMs), magnetic gear, vernier machines.

I. INTRODUCTION

THE MAGNETIC-FIELD modulated principle or called magnetic gearing effect was first applied to magnetic gears [1]. In recent, the inherent magnetic gearing-based electrical machines, including flux modulated machines (FMMs), flux switching PM machines, and flux reversal PM machines (FRPMs), have been gaining more attention for their comparable high torque density [2]. The FMMs [3], and the partitioned stator flux reversal PM machines (PS-FRPMs) which are derived from the regular FRPMs [4], comprise three parts: stationary stator with armature winding, permanent magnet rotor (called partitioned stator in PS-FRPMs), and iron flux modulation pole.

To date, the previous studies on FMMs and PS-FRPMs mainly focus on the operation principle, design optimization, power factor, and so on. Also, some studies deal with the torque density improvement [3]–[6]. Generally, the armature current of synchronous machines are pure sinusoidal. In [7]–[10], a dc-biased sinusoidal current is applied to variable flux reluctance machine and permanent magnet machine. The theoretical analysis about the principle was analyzed in [7]. It is proven that the dc current can produce an exciting field to produce torque with the ac current.

As an extension of the work in [10], this paper applies the dc-biased current to FMMs for torque density improvement. Compared with the regular pure sinusoidal current for FMMs, the dc current biased sinusoidal current is injected into the specifically arranged armature coils, while the machine structure remains the same. By the theoretical and finite-element analysis (FEA), the operation principle and the electromagnetic performance are analyzed. The results show that on the premise of constant copper loss, the torque density is improved. Furthermore, the flux adjustment capability is greatly enhanced, since the exciting field can be easily adjusted by the injected dc current.

II. MACHINE TOPOLOGY, INVERTER CIRCUITS, AND OPERATION PRINCIPLE

A. Machine Topology and Coil Connection

A feasible machine is shown in Fig. 1 to illustrate the topology and coil connections. It has 12 stator-slots, 10 iron-modulation-poles, and 6 PM pole pairs. The number of armature winding pole pairs \( P_a \) is 4. The outer stator has nonoverlapping concentrated winding which has short end-connection, the rotating iron-segment is inserted in the air gap between the outer and inner stator, and the inner stator is with surface mounted magnets. The structure is similar to PS-FRPM with surface mounted PMs, and FMM in which the flux modulation iron is rotating. The main novelty of the proposed machine is that the dc current is injected into the armature winding. In order to form the path of dc current, the coils of each phase are divided into two groups. Taking an example of Phase A, the coil A1 and A3 make up sub-phase A+, and are fed with positive dc current, while the coil A2 and A3 make up...
sub-phase A— which are fed with dc current with appositive direction. Similarly, the coil arrangement for phases B and C can be achieved.

**B. Main Inverter Circuits**

The inverter circuit that can provide the required current is similar to six-phase half bridge inverter, and the connection of inverter and machine winding terminals is shown in Fig. 2. The dc-biased sinusoidal phase currents are expressed as

\[
i_{A+} = \sqrt{2} I_{ac} \sin(w_{et} + \alpha) + I_{dc}
\]

\[
i_{A-} = \sqrt{2} I_{ac} \sin(w_{et} + \alpha) - I_{dc}
\]

\[
i_{B+} = \sqrt{2} I_{ac} \sin(w_{et} + \alpha - \frac{2}{3} \pi) + I_{dc}
\]

\[
i_{B-} = \sqrt{2} I_{ac} \sin(w_{et} + \alpha - \frac{2}{3} \pi) - I_{dc}
\]

\[
i_{C+} = \sqrt{2} I_{ac} \sin(w_{et} + \alpha + \frac{2}{3} \pi) + I_{dc}
\]

\[
i_{C-} = \sqrt{2} I_{ac} \sin(w_{et} + \alpha + \frac{2}{3} \pi) - I_{dc}
\]  

(1)

where \(I_{ac}\) and \(I_{dc}\) are the root-mean-square (rms) values of the ac and dc component, and \(w_{e}\) is the electrical angular velocity.

The electrical and mechanical angular velocities satisfy the following relationship:

\[
w_{e} = N_r w_{r} = N_r (2\pi \frac{n}{60})
\]  

(2)

where \(N_r\) is the number of rotor slots.

**C. Operation Principle**

The proposed machine fed with dc-biased current can be considered as the superposition of PS-FRPM and vernier reluctance machine fed with dc biased sinusoidal current [6]. For PS-FRPM, the stationary magnetic motive force (MMF) produced by the PM is modulated by the rotating permeance of iron segment, and a rotating exciting field is produced. The pole pair relationship is

\[
P_a = |P_{PM} - N_r|
\]  

(3)

where \(P_a\) is the armature winding pole pair number and \(P_{pm}\) is the PM pole pair number.

In addition to the PM torque, the novelty of the proposed machine is to generate another stationary MMF around the air-gap circumference by injecting dc current in armature winding, and with the permeance modulation effect of iron segment, another exciting field is generated. Moreover, the total exciting field can be adjusted by the dc current. Similarly, the following equation should be satisfied:

\[
P_a = |P_{dc} - N_r|
\]  

(4)

where \(P_{dc}\) is the pole pair number of MMF by dc current.

In the proposed machine shown in Fig. 1, the pole pair number of the MMF by the dc current \(P_{dc}\) is 6.

Generally, the maximum torque per current control of FMMs and PS-FRPMs is zero \(-d\)-axis current. Therefore, the electromagnetic torque expression under \(I_d = 0\) control of the proposed machine can be written as

\[
T_{em} = N_r (\psi_{pm} + \psi_{dc}) I_q = N_r \psi_{pm} I_{ac} + N_r I_{dc} L_m I_{ac}
\]  

(5)

where \(\psi_{pm}\) and \(\psi_{dc}\) are the flux linkage by PM and dc current, respectively, and \(L_m\) is the equivalent magnetizing inductance.

It can be found that compared with the regular FMMs and PS-FRPMs, in addition to the existing PM torque, another torque component that is proportional to the square of current is introduced.

**III. FEA VERIFICATION**

In this section, FMMs fed with dc-biased current is analyzed with FEA. A machine in Fig. 1 is built to verify the theoretical analysis. The main parameters are shown in Table I.

**A. Exciting Field Analysis**

The no load flux plot distributions with different excitation conditions when the phase A flux linkage is maximum are compared in Fig. 3. As shown, when only with PM excitation, the flux produced by the PM is modulated by the iron segment, and then flows into the outer stator, that is to say, the flux flows across the two air gap. While when only with the dc current, and the PMs are removed, the flux produced by dc current is modulated by iron segment, and then return back to outer stator, that is to say, the flux flows across only the outer air gap. Neglecting the iron saturation effect, when both the dc current and PM are excited, the flux distribution can be conceptually considered as the superposition of the condition in Fig. 3(a) and (b).

The air-gap flux densities with the aforesaid three excitation conditions are analyzed in Fig. 4. The fourth and eighth harmonics are the rotating working components, while the
Fig. 3. Flux plot distributions simulated with FEA. (a) PM excitation only. (b) DC current of 3 A excitation, PMs are removed. (c) Both dc current of 3 A and PM excitation.

sixth harmonic is the stationary component. It can be found that by adding dc current of 3 A into the armature winding, the working exciting fields can be enhanced and the stationary components can be reduced. This proves that the dc current can improve the field adjustment capability and the flux utilization.

B. Virtual Back EMF Analysis

Fig. 5(a) compares the simulated phase A back EMF waveforms with different excitation conditions. As shown, the phase angle of back EMF produced by the dc current aligns with that by PM. Besides, it can be found that the back EMF can be adjusted flexibly by the dc current. Moreover, from Fig. 5(b), it can be found that the main harmonics of the back EMF are fifth and seventh.

C. On Load Flux Distribution Analysis

As mentioned before, both the fields produced by PM and dc current can interact with ac current in armature winding to generate average torque. Fig. 6 compares the on-load flux distributions with different excitation conditions simulated by FEA. When fed with pure sinusoidal ac current, this machine is the regular FMM or PS-FRPM [4], as the flux distribution shown in Fig. 6(a). While when fed with both dc and ac current in winding, and assuming the PM is vacuum, at this time this machine can be seen as dc-biased sinusoidal vernier reluctance machine [7], as the flux distribution shown in Fig. 6(b). The third situation is when fed with both dc and ac current in winding, and considering the PM remanence, at this time this machine can be seen as superposition of FMM or PS-FRPM with dc-biased sinusoidal vernier reluctance machine.

D. Electromagnetic Torque Waveform

It is necessary to compare the torque performance with regular pure sinusoidal current and dc-biased sinusoidal current. As shown in Fig. 7, under constant phase current, the average
torque with dc biased phase current (dc component is 3 A and ac component is 7.4 A) is 12% higher than that with regular pure sinusoidal current. This proves that with the proposed dc-biased current, the torque density can be improved. This phenomenon is because with dc-biased current, although the reduced ac current results in the decrease of PM torque, the emerging dc current can interact with ac current to produce more torque, which can compensate the reduction of permanent magnet torque. Also, it can be found that the torque waveforms are similar and the torque ripple is nearly the same.

IV. OPTIMAL INJECTED DC CURRENT

It has been demonstrated that with the proposed dc-biased current, the torque is increasing. To further understand the optimal injected dc current in phase current to achieve a maximum torque improvement, the dc current ratio is defined

\[ I_{dc} = k I_{rms} \]
\[ I_{ac} = \sqrt{1 - k^2} I_{rms} \] (6)

where \( k \) is the defined dc current ratio. The high \( k \), the high biased level in the phase current waveform.

Substituting (6) into (5), the torque expression in respecting to dc current ratio becomes

\[ T_{em} = N_r \psi_{pm} \sqrt{1 - k^2} I_{rms} + N_r L_m k \sqrt{1 - k^2} I_{rms}^2 \] (7)

The optimal dc current ratio can be obtained by differentiating the torque, and letting the differential result be zero

\[ \frac{\partial T_{em}}{\partial k} = 0. \] (8)

Fig. 8 shows the torque variation with dc current ratio under various phase currents. It can be found that, the torque first increases, then reaching the maximum value, and after that the torque decreases. At a certain point, the torque may be less than that without dc current injection. In an extreme case, there is no average torque when the phase current contains only dc current. In a word, with dc-biased current, the torque density is improved. Also, it is found that the regular pure sinusoidal current is not the optimal condition in terms of torque density.

Fig. 9 shows the torque and the optimal current configuration variation with phase current by the FEA. As shown, with the proposed dc-biased current, the torque increases in the entire range. In addition, the optimal dc current ratio increases at first, and then decreases. The second torque component in Eq. (7) is proportional to the square of current while the PM torque component is proportional to the current. Therefore, when the iron is not saturated, the emerging torque component increases faster, and hence, more dc current is required. However, when the iron is saturated, the emerging torque is more seriously affected by the iron saturation, since its magnetic path does not pass through the permanent magnet.

As illustrated in (7), the torque increase is also related with the PM flux linkage, which is determined by the PM remanence. Fig. 10 shows the simulated torque improvement ratio and optimal current configuration variation with different PM remanences. It can be found that, the poorer PM magnetic performance, the higher torque improvement ratio, and the more dc component is required.

The required current is smaller considering the higher torque density, and thus, the copper loss is reduced. Besides, the iron
losses and PM loss are nearly the same, and therefore, it is foreseeable that the efficiency will be improved under constant.

V. Conclusion

In this paper, the performance of FMMs fed with dc-biased sinusoidal current is analyzed theoretically and with FEA. The analysis results show that with the proposed dc-biased current, the torque density and the efficiency of the existing FMMs can be improved further. In addition, the torque increase is related with the PM remanence and phase current. The poorer PM remanence or the higher phase current, the higher torque improvement ratio. For FMMs adopting NdFeB magnets and natural cooling technology, the torque density may increase more than 10% generally.

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References
