Comparative Study of Electromagnetic Performance of Double-tooth Variable Flux Memory Machine

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Abstract. Aiming at the problem of the low electromagnetic torque performance of the traditional Variable Flux Memory Machine (VFMM), a novel double-tooth Variable Flux Memory Machine is proposed in this paper. Firstly, the topology and operation principle of the novel double-tooth VFMM are introduced. By using the 2-D finite element analysis method, the open circuit characteristics of the novel double-tooth VFMM and the traditional single-tooth VFMM with low coercive force (LCF) in different magnetization states are compared and analysed, and the electromagnetic torque in the flux-enhanced state is compared and studied. In addition, the efficiency maps of double-tooth VFMM are investigated. Compared with the traditional single-tooth VFMM, the flux adjustment ability of the double-tooth VFMM is more than doubled, and the electromagnetic torque under the same current is increased by 21.8%. The results show that the double-tooth VFMM has better flux adjustment ability and larger electromagnetic torque.

1. Introduction

Recently, with the improvement of magnetic properties of permanent magnet materials, permanent magnet synchronous machine is widely used in electric vehicles, wind power generation, aerospace and other fields due to its small size, light weight and high efficiency. However, it is difficult to adjust the air gap flux field of the machine due to the permanent magnet excitation. The memory machine combines the advantages of the electric excitation machine and the permanent magnet machine, the magnetic field of the LCF PMs are adjusted by the current pulse which reduces the copper consumption of the excitation. By changing the directions of LCF PMs, the purpose of increasing torque density and expanding speed range can be achieved [1].

Based on the structure of doubly salient machine, variable flux reluctance machine (VFRM) is proposed [2]. The machine provides excitation field for the machine through magnetizing coil, which has flexible flux adjustment ability and good flux weakening performance. In [3], a permanent magnet synchronous machine with permanent magnet in the stator yoke is proposed. The magnetizing coil of VFRM is replaced by permanent magnet. Compared with VFRM, the electromagnetic torque is increased, but the ability of flux adjustment is lost. In order to improve the torque density and flux adjustment performance of the machine, the doubly salient hybrid excitation machine is studied in [4]...
and [5] on the basis of VFRM. In addition to the method of adding magnetizing coil to the permanent magnet synchronous machine, adding NdFeB series or parallel low LCF permanent magnet to the permanent magnet synchronous machine can also increase the flux adjustment ability of the machine. In [6] and [7], many kinds of memory machines are studied. Compared with the traditional permanent magnet synchronous machine, those memory machine have flexible flux adjustment ability. Compared with the hybrid excited machine, they use LCF permanent magnet for flux adjustment, which reduce the loss of magnetizing coil and improve the efficiency. Therefore, based on the topology of VFRM and combined with the advantages of memory machine and permanent magnet synchronous machine, 6/13 VFMM is proposed [7]. Since the multi tooth stator structure can improve the torque performance of the machine, a multi tooth stator structure with good torque performance is proposed [8]. Therefore, a novel double-tooth VFMM is designed and optimized in this paper. Moreover, the topology and operation principle of proposed machine are introduced, and the performances of VFMM such as flux adjustment ability and torque performance are investigated. In addition, efficiency maps of double-tooth are studied. The results show that better flux adjustment capability and larger torque performance can be obtained in novel double-tooth VFMM.

2. Principle and machine topologies

![Figure 1. Topologies of VFMM.](a) Single-tooth. (b) Double-tooth.)

![Figure 2. Simplified magnetic circuit model.](a) Flux enhanced. (b) Flux weakened.)

The topologies of VFMM having single-tooth and double-tooth are shown in Figure 1. Armature winding adopts concentrated winding, the tangential magnetized NdFeB is embedded in the inner yoke of the stator. The LCF PMs with bipolar and the magnetizing coil are sandwiched between the outer stator and inner stator. In order to compare the electromagnetic performance of the two machines, it is necessary to keep the outer diameter, stack length, air gap length and the volume of the two permanent magnets consistent. The basic parameters of two VFMMs are shown in Table 1.

| Parameters             | Single-tooth | Double-tooth | Parameters             | Single-tooth | Double-tooth |
|------------------------|--------------|--------------|------------------------|--------------|--------------|
| Stator outer radius ,mm| 45           | 45           | Stator big tooth width ,mm | 7            | 8            |
| Stack length ,mm       | 25           | 25           | Split ratio            | 0.6          | 0.6          |
| Stator/rotor poles     | 6/13         | 6/13         | Turns per coil(AC/DC)  | 42/50        | 42/50        |
| NdFeB volume ,mm³      | 10.8×4       | 10×4.3       | Pole arc coefficient   | 1/3          | 1/3          |
| LCF PMs volume ,mm³    | 7.2×3.75     | 9×3          | Rated speed ,r/min     | 400          | 400          |
| Stator small tooth width ,mm | -            | 4            | DC-link voltage ,V      | 20           | 20           |
| Air gap ,mm            | 0.5          | 0.5          | Rated current ,A        | 10           | 10           |
Figure 2. Shows the simplified magnetic circuit of VFMM of magnetization and demagnetization, where \( F_{pm} \) and \( F_{lcf} \) are the MMF generated by NdFeB and LCF PMs respectively, where \( R_{pm} \), \( R_{lcf} \) and \( R_g \) are the magnetic resistance of NdFeB, LCF PMs and air gap respectively. The magnetization direction of LCF PMs can be changed by applying current pulses in different directions to the LCF PMs through the magnetizing coil, so as to improve the flux adjustment ability of the machine.

![Figure 2](image)

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![Figure 3](image)

**Figure 3.** Field distributions of the double-tooth VFMM. (a) Flux enhanced. (b) Zero magnetization. (c) Flux weakened.

Figure 3. shows the field distribution of double-tooth VFMM under different magnetization states of LCF PMs, and the direction of arrow is the magnetization direction of PMs. With the same or opposite magnetization direction of LCF PMs and NdFeB, the air gap flux field is flexibly modulated. It can be seen that under the flux-enhanced state, all the magnetic fields generated by LCF PMs and NdFeB pass through the air gap, and the energy exchanged between the stator and rotor increases. LCF permanent magnet makes the magnetic short circuit between the outer yoke and the inner yoke of stator under the flux-weakened state. While the flux density of air gap decreases, the exchange energy between stator and rotor decreases. Under the zero-magnetization state, the open circuit air gap magnetic field is mainly provided by NdFeB, and the LCF PMs are under the fully demagnetized state.

3. Electromagnetic performance comparison

3.1. Flux adjustment ability

Because of the double tooth stator structure of the double-tooth VFMM, the air gap flux density appears more wrinkles. Figure 4 (a) and (b) show the air gap flux density of two kinds of VFMM respectively. It can be seen that the air gap flux density can be adjusted by changing the magnetization state of LCF PMs. Figure 4(c) and (d) show the flux linkage of two kinds of VFMM in different magnetization states. From the figure, we can obtain flux adjustment ability of the two kinds of VFMM.
In order to compare the flux adjustment ability of two kinds of VFMM, the flux adjustment capability of VFMM can be predicted by the flux adjustable ratio $k_f$, which is defined by

$$k_f = \frac{\psi_{\text{max}} - \psi_{\text{min}}}{\psi_{\text{pm}}} = \frac{\Delta \psi}{\psi_{\text{pm}}} \quad (1)$$

Where the $\psi_{\text{max}}$, $\psi_{\text{min}}$ and $\psi_{\text{pm}}$ respectively represent the amplitude of flux linkage when the LCF PMs are under flux-enhanced state, flux-weakened state and zero-magnetization state. The flux adjustable ratio $k_f$ of single-tooth VFMM and double-tooth VFMM are 0.670 and 1.554 respectively, which indicates double-tooth VFMM has a better flux adjustment ability.

Since the double-tooth VFMM has a wider range of flux adjustment, the open circuit back EMF of the double-tooth VFMM is larger than that of the single-tooth VFMM under flux-enhanced state, and smaller under flux-weakened state, as shown in Figure 4(e) and (f). In addition, from Figure 4(e) and (f), it can be seen that the back EMF waveform of the double tooth VFMM tends to be more sinusoidal and the harmonic is less.

3.2. Torque performance

Figure 5 (a) shows the curve of electromagnetic torque changing with the current angle. It can be seen that the two kinds of VFMM obtain the maximum electromagnetic torque when the current angle is about 0°, which means that the d-axis inductance and q-axis inductance of VFMM are approximately equal, so the reluctance torque can be negligible. Figure 5 (b) shows the electromagnetic torque of two kinds of VFMM. From the figure, the double-tooth VFMM has larger electromagnetic torque performance and smaller torque ripple than the single-tooth VFMM. Compared with single-tooth VFMM, the electromagnetic torque of double tooth VFMM is increased by 21.8%. Figure 5 (c) shows the curve of two kinds of VFMM electromagnetic torque against current. The double-tooth VFMM increases the flux path and reduces the electromagnetic saturation of stator teeth. Therefore, it can be seen from the figure that with the increase of current, the double-tooth VFMM is far less affected by q-axis current than single-tooth VFMM. It demonstrates that the double-tooth VFMM exhibits larger torque regardless of loads.
Figure 5. Torque characteristics of VFMM with single-tooth and double-tooth under flux-enhanced state. (a) Torque-Current angle waveform, phase current=10A. (b) Steady-Torque waveform, $I_q=10A$. (c) Torque-Current waveform.

3.3. Efficiency maps

Figure 6. Efficiency maps of the double-tooth VFMM under different states. (a) Flux enhanced. (b) Flux weakened. (DC link voltage=20V and rated current=10A.)

Because the double-tooth VFMM exhibits larger torque ability and better flux adjustment capability than the traditional single-tooth VFMM, the efficiency of double-tooth VFMM will be investigated. The efficiency maps are drawn under different states in Figure.6. It can be seen that the flux-enhanced state is conducive to the efficient operation of the constant torque area, and the weak-magnetic state is conducive to the efficient operation of the machine in the constant power area. Therefore, the proposed double-tooth VFMM can obtains high efficiency with a wide range of torque and speed by changing directions of LCF PMs.

4. Conclusion

In this paper, the topology and operation principle of VFMM are firstly introduced. Then, a comparative study of the novel double-tooth VFMM and traditional single-tooth VFMM are presented. The efficiency maps are investigated. The results show that the level of saturation of the machine is reduced because of the dual-tooth structure of the double-tooth VFMM, which increases the flux path. In addition, the double-toothed structure of the machine shortens the air-gap path, which leads to an improvement in the flux adjustment ability and output torque capability. Moreover, the results show that the double-tooth machine can operate effectively within a wide range of speed and torque under different magnetization states.

Acknowledgments

This work was financially supported by National Natural Science Foundation of China [grant numbers 51507045].

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