



Article Design of a Chamfered Structure on Consequent-Pole Vernier Permanent-Magnet Machine

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Abstract: The consequent-pole (CP) Vernier permanent-magnet (VPM) machine has been developed over the last decade. In VPM machine, the CP structure can produce considerable torque with a half volumn of the PMs compared with the regular structure, so the cost is reduced and the mechanical strength is increased. In this paper, an improvement of chamfering structure on a CPVPM machine is proposed to alleviate the flux leakage and increase the torque density. The chamfered structure is easily machined and will not influence the robustness of the rotor. The comparison results show that under the same volume and copper loss constraint, the proposed structure has smaller cogging torque, smaller torque ripple, larger torque density and larger power factor.

Keywords: consequent-pole; permanent-magnet machine; Vernier machine



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1. Introduction

Due to the flux modulation effect, the Vernier permanent-magnet (VPM) machine can produce large torque with low mechanical speed. The characteristics make it a promising candidate in the future industrial fields. The direct-driving feature means that VPM machine can be applied without a gear box, which not only improves the reliability of the whole system but also increases the efficiency. For these reasons, even if the topology has relatively low power factor, the VPM machine is still extensively employed in many applications, such as wind power generation, electric vehicle, aerospace, etc.

In recent years, many works have been conducted on the research of novel VPM machine topologies. Among them, the consequent-pole (CP) structure has been attracting more attention because it can save nearly half of PM usage. In [1], the CP structure is firstly proposed, in which the stator PM is also employed. In [2–4], the CP structure is combined with flux reversal machines. Furthermore, the CP structure can also be combined with many common topologies, such as modular stator [5,6], double-stator [7], toroidal winding [8], Halbach PM [9], and axial flux structure [10].

As can be seen in Figure 1, compared with regular VPM structure, the CP structure saves nearly half of the PMs. The remaining PMs have the same polarity, and the iron teeth are sandwiched between the PMs, which can be called the flux modulation poles (FMPs). For compensation, the pole-arc of PMs in the CPVPM machine will be larger than that in regular VPM machine. The FMPs work as the PMs of opposite polarity. Although the FMPs do not provide magneto-motive force (MMF), their relative permeability is much larger than that of PMs. In this way, the CPVPM machine can produce considerable torque with the half volumn of PMs, which are expensive and have poor mechanical properties.

In this paper, a chamfering structure is proposed for a CPVPM machine, which is shown in Figure 2. As can be seen, the chamfered structure is applied on the CP adjacent to the PMs. According to the investigation and comparison in this paper, the minor improvement on the silicon steel can alleviate the flux leakage problem and increase the torque density under the same conditions. Moreover, the chamfering processing technology is very simple and will not influence the mechanical strength of the rotor. The main contribution of this paper is to improve the performances of the CPVPM machine with a novel chamfered structure, and to discuss the advantages of the proposed structure by comparing it with the regular CPVPM machine. The concept of the shape improvement on the rotor pole has been researched in some articles [11–13]. However, the proposed structure differs in machine structure and the chamfering method. In [11], an air space is proposed between the PM and the iron pole but the chance will reduce the average torque as well as the torque ripple. The chamfered structure proposed in this paper can increase the average torque when the torque ripple is still reduced. In [13], a pole shaping method was proposed to improve the CP machine performances, but the proposed pole shape is not easy to manufacture. Furthermore, in this paper, the chamfered structure is applied in the VPM machine, which relys on the modulated flux density and will show quite different effects compared with the normal PMSM machine.

The finite element analysis (FEA) results show that the proposed structure has advantages under the open-circuit condition and on-load condition with copper loss up to 100 W.

This paper is organized as follows. In Section 2, the structure and operation principle of the proposed chamfering structure are illustrated. In Section 3, the electromagnetic performances of the regular CPVPM machine and the proposed chamfered CPVPM machine are compared. In Section 4, the influences of some key parameters on the torque capability are discussed. Section 5 concludes this paper.



Figure 1. Comparison of both structures. (a) Regular VPM machine; (b) CP VPM machine.



Figure 2. Comparison of CP structures. (a) Regular CP structure; (b) Chamfered CP structure.

2. Machine Structure and Operation Principle

The operation principle of the chamfered structure is illustrated in Figure 3. As can be seen, in regular CP structure, the flux leakage between the PMs and the rotor teeth is very severe, which wastes part of the MMF of the PMs. In the proposed chamfered structure, the magnetic path between the adjacent PMs and rotor teeth is lengthened. In this way, the flux leakage can be alleviated. As is shown in Figure 3b, the flux lines are more apt to cross the air-gap, so the working flux linkage can be increased.

To further explain the working mechanism of the chamfered structure, a comparison of the ideal open-circuit condition between the regular CP structure and the proposed CP structure is performed. The parameters of both topologies are shown in Table 1. It is worth mentioning that, in this comparison, the iron core is set as unsaturated. To achieve that, the relative permeability of the iron core material is set to 10,000 and remains unchanged.



Figure 3. Flux line distribution. (a) Regular CP structure; (b) Chamfered CP structure.

Table 1. Design parameters of both machines.

Parameters	Regular Structure	Proposed Structure
Stator outer diameter	120 mm	120 mm
Split ratio	0.65	0.65
Stator slot number	12	12
Rotor slot number	11	11
Air-gap length	1 mm	1 mm
Tooth width	7.1 mm	7.1 mm
Chamfer length	-	1.5 mm
Chamfer arc	-	2.4 deg
PM thickness	4.4 mm	4.4 mm
PM arc	20.62 deg	20.62 deg
PM type	NMX-S38EH (60 °C)	NMX-S38EH (60 °C)
Silicon steel type	$\mu_r = 10,000$	$\mu_r = 10,000$

The ideal air-gap flux density is represented as [14]:

$$B(\theta) = B_m(\theta) \cdot \frac{\Lambda(\theta)}{\mu_0/g'},\tag{1}$$

where $B_m(\theta)$ is the ideal air-gap flux density distribution ignoring the stator slotting effect, and $\Lambda(\theta)$ is the air-gap permeance ignoring the rotor slotting effect.

It is noticed that in Table 1, that the regular structure and the chamfered structure have the same split ratio and stator tooth width, so the stator structure of both machines are exactly the same. The plot and harmonic spectrum of $\Lambda(\theta)$ is given in Figure 4.

Similarly, the $B_m(\theta)$ plots and spectra of both regular and proposed CP structures are given in Figure 5.

From Figure 5b, it is found that the first and second order harmonics of the proposed structure are both larger than that of the regular structure. The results accord with the aforementioned design concept that the proposed structure can increase the effective flux lines. The air-gap flux density of both structures is calculated based on (1), as is shown in Figure 6.

According to the flux modulation principle [15], both the fundamental and modulated components of the flux density influence the induced voltage in the coil. From Figure 6, it can be found that the proposed structure has larger fundamental harmonic (eleventh order) and modulated harmonic (first order). It is concluded from the ideal condition that the chamfered CP structure has an advantage over the regular CP structure. Meanwhile, the proposed improvement on the CP is very simple and will not influence the mechanical strength of the rotor.



Figure 4. Stator permeance in regular VPM structure with infinite permeability. (**a**) Permeance plot; (**b**) Permeance spectrum.



Figure 5. Rotor relative MMF in both structures with infinite permeability. (**a**) Permeance plot; (**b**) Permeance spectrum.



Figure 6. Air-gap flux density in both structures with infinite permeability. (**a**) Permeance plot; (**b**) Permeance spectrum.

3. Performances Comparison

In this section, the detailed electromagnetic performances of regular CP structure and the proposed CP structure are compared under the on-load condition. The corresponding parameters are given in Table 2, where both topologies are globally optimized for largest average torque with the constraint of 20 W copper loss. As can be seen, in this section, the silicon steel is not a more ideal material.

The flux contour distributions of the proposed machine and the regular candidate are shown in Figure 7. As is illustrated, in the proposed topology, the saturation in the stator yoke is alleviated. In Figure 7a, there are some saturation regions in the rotor teeth, which is exactly the chamfered part. In Figure 7b, the saturation problem does not exist. The flux lines also show that the flux leakage in the rotor is reduced.

The comparison of torque performances is given in Figure 8. As Figure 8b shows, the cogging torque magnitude of the regular CP structure is 25 mNm, and that of the proposed structure is only 6 mNm. It indicates that the proposed structure has an inherent property of low torque ripple. The average torque of the regular CP structure is 13.4 Nm, and that of the proposed structure is 14.0 Nm. The peak-to-peak value of torque ripple of regular CP structure is 0.18 Nm, and that of the proposed structure is 0.1 Nm. Figure 8a shows that the chamfered structure can provide larger torque with a lower torque ripple.

It should also be noticed that, as can be calculated from Table 2, the PM volume of the regular CP structure is 32 cm³, and that of the proposed structure is 35 cm³. From the ponit of view of PM usage effectiveness, the chamfered structure is not good as the regular structure.

Parameters	Regular Structure	Proposed Structure
Stator outer diameter	120 mm	120 mm
Split ratio	0.65	0.65
Stator slot number	12	12
Rotor slot number	11	11
Air-gap length	1 mm	1 mm
Core length	50 mm	50 mm
Tooth width	7.1 mm	7.1 mm
Chamfer length	-	1.5 mm
Chamfer arc	-	2.4 deg
Coil turns per phase	100	100
Per slot area	173.0 mm ²	173.0 mm ²
PM thickness	4.4 mm	5 mm
PM arc	20.62 deg	19.96 deg
PM type	NMX-S38EH (60 °C)	NMX-S38EH (60 °C)
Silicon steel type	35WW400	35WW400

Table 2. Design parameters of both machines.



Figure 7. Flux contour distributions of both candidates under 20 W copper loss. (**a**) Regular machine; (**b**) Proposed machine.



Figure 8. Torque performances of both candidates. (a) Torque; (b) Cogging torque.

The over-loading capability of both candidates is also compared. As can be seen in Figure 9a, when the copper loss increases, the saturation problem in both candidates gradually becomes severe. However, the average torque of the proposed structure is always larger than that of the regular CP structure, and the gap between two curves gradually increases.

Figure 9b shows that when the mechanical speed remains constant, the power factor decreases with the copper loss. The proposed structure has a higher power factor over the whole loss range, the reason of which is that the proposed structure has less flux leakage.



Figure 9. Over-loading capability of both candidates. (a) Average torque; (b) Power factor.

Furthermore, the demagnetized back-EMF characteristics of both candidates are also compared. Taking the 20 W working condition for example, if the $i_d = 0$ control strategy is adopted, the value of i_q is 9.7 A. If the three-phase short circuit fault happens, the peak d-axis current is -28.6 A. As is shown in Figure 10, after current demagnetization, the back-EMF drop of the proposed machine is 5.5%, and that of the regular machine is 7.3%. The results show that the chamfered structure is also beneficial to the anti-demagnetization characteristic of CPVPM machine.



Figure 10. Back-EMF of both candidates before and after current demagnetization. (**a**) Proposed structure; (**b**) Regular structure.

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4. Parameter Optimization

In this section, the influences of several machine sizes are investigated. To make sure that the optimization process is fair, the copper loss is fixed at 20 W.

4.1. Split Ratio (SR)

The magnetic energy is stored in the air-gap. If the SR is too small, then the converted magnetic energy is decreased. As a result, the torque will be decreased. If the SR is too large, the stator yoke will be thinner, so the magnetic saturation problem will be more severe. The SR needs to be optimized carefully. As Figure 11 shows, if the SR is large, the torque can be reduced, but if the SR is too small, the torque is decreased since the air-gap volumn is too small to store the magnetic energy. According to the results, the best SR is chosen as 0.65.



Figure 11. Relationship between split ratio and average torque.

4.2. PM Thickness

If the PM thickness is too small, then the magnetic motive force (MMF) is too small, so the flux density is small, but if the PM thickness is too large, the flux density cannot increase accordingly since the relative permeability of the PM material is close to vacuum. The PM material is really expensive, so the value of the PM thickness needs to be optimized. The optimization result is given in Figure 12. When the PM thickness is very large, as expected, the torque is reduced because the effective air-gap is longer. Moreover, the saturation problem will gradually come into being. The optimal value of the PM thickness is 5 mm.



Figure 12. Relationship between PM thickness and average torque.

4.3. Tooth/PM Width

Essentially, the stator tooth and PM width influences the allocation between winding current and magnetic flux. The influence of combinations of stator tooth width and rotor PM width is shown in Figure 13, where each curve represents a tooth width. From the plots it can be found that, the stator teeth width cannot be too small, because it will cause the saturation problem. If the stator teeth width is too large, the place for stator winding will be reduced. As can be concluded, the 19.8 degree/7.2 mm combination is the optimal choice.



Figure 13. Relationship between tooth/PM width combination and average torque.

4.4. Stator Tooth Length

The stator tooth length is another valuable parameter. It will influence the thickness of the stator yoke and armature winding area. When the tooth length gets larger, the stator yoke will be thinner. Consequently, the saturation problem will also restrict the torque production. As is shown in Figure 14, the optimal value of the tooth length is 11 mm.



Figure 14. Relationship between tooth length and average torque.

4.5. Chamfer Shape

Last but not least, the the impact of chamfer shape on average torque is given in Figure 15. As has been discussed in Section 2, the chamfer shape can change the harmonic amplitude of the air-gap permeance and influence the produced torque. As can be seen, the chamfer shape with 2.4 degree width and 1.5 mm length is the most suitable combination.



Figure 15. Relationship between chamfer shape and average torque.

5. Discussion

In this paper, a chamfered structure is proposed for the CPVPM machine. The operation principle is firstly investigated by ideal open-circuit condition comparison, and it is found that the proposed structure can alleviate the flux leakage and increase the effective flux lines. Next, the on-load condition comparison with the regular CPVPM machine is performed under the 20 W copper loss condition. The results show that the proposed structure has smaller cogging torque, smaller torque ripple, larger torque density, and larger power factor. The optimization process of some key parameters is also discussed in the paper. It is concluded that the chamfered structure has the ability to increase the torque capability without influencing the mechanical strength.

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