Cogging Torque Reduction in Surface-mounted Permanent Magnet Synchronous Motor by Axial Pole Pairing

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Abstract

In many machines, where permanent magnets are used, the effects due to cogging torque generated by permanent magnets (PMs) aggravate the output characteristics of the machines. This paper presents the method for reducing cogging torque in surface-mounted permanent magnet synchronous motor (SPMSM). A new cogging torque suppression method called axial pole pairing is proposed. Compared to conventional pole pairing, axial stack length is considered. Analytical formulas are used to estimate cogging torque and verify the validity of axial pole pairing. Characteristics of cogging torque are investigated on various combinations of axial pole pairing. From this result, improvement on space harmonic analysis has been researched about SPMSM for reducing cogging torque.

Keywords: Axial Pole Pairing, Cogging Torque Reduction, Space Harmonic Analysis (SHA), Surface-mounted Permanent Magnet Synchronous Motor (SPMSM)

1 Introduction

Surface-mounted permanent synchronous motors (SPMSM) are widely used in industrial applications with the high torque density and high efficiency as well as the simple structure they exist. In many of these applications, the high strength of permanent magnets not only leads to generating remarkably high torque but also causes the undesirable effects of high cogging torque that can aggravate performance of motor. Generally the cogging torque arises when the gap of magnetic reluctances between the rotor magnet and slotted stator exists \cite{1}. Design parameters that affect to the magnitude of cogging torque can be slot openings, the number of slots per phase, thickness of teeth, width of slot, pole ratio of PMs, and length of air gap, etc. Minimization of cogging torque generation is accordingly of great importance \cite{2}.

Analytical studies of cogging torque prediction in surface mounted permanent magnet (PM) machines are well documented \cite{3}-\cite{8}, and various methods of cogging torque reduction based on different models have been analysed \cite{9}-\cite{12}. Suppression of cogging torque invariably leads to some degree of compromise in the performance of the machine, as well as cost penalties in implementation. For example, by adjusting magnet pole arc, not only the cogging torque but also the back electromotive force (EMF) can be reduced simultaneously. Thus, it is noteworthy that each approach has its own limitations, and some are far more difficult to implement than others.

In this paper a new cogging torque suppression method called axial pole pairing is proposed. It is a new technique to enable coils to be connected in parallel, and can comprise different axial lengths as well as different pole arc widths. In conclusion,
the axial pole pairing is referred to several different-axial-length machines with the same stator configuration axially adjoined [13].

Finally the estimated result by using the presented method shows the trend map of model parameters according to the variation of combined axial pole pairing. The result maps can effectively give designers the wide insights when the desired parameters are selected.

2 Cogging Torque Analysis in SPMSM

The two torque components affect output performance of SPMSM: Torque ripple and Cogging torque. The former is produced from the harmonic content of the input current and voltage wave, and the latter is produced by the magnetic attraction between the rotor mounted PM and the stator teeth in the machine. In this paper, cogging torque reduction is considered to improve the output performance of SPMSM Therefore cogging torque is first calculated by using space harmonic analysis (SHA), and the axial pole pairing is adopted to reduce the cogging torque. Fig.1 shows a schematic of the SPM motor used for analysis.

2.1 Calculation of Cogging Torque

To reduce cogging torque, analytical estimation of cogging torque should precede any process. SHA is a reliable means of estimating the likely level of cogging and its dependence on the motor design parameters [14]. Characteristic of cogging torque are analysed by using the concept of relative permeance in this paper, based on those following assumptions:

- The permeability of core is infinite;
- Slots are simplified to a rectangular shape;
- Magnetic field distribution is determined by magnetic field and relative permeance;
- Stator surface is smooth for 2-D solution;
- Flux crosses the magnet and air-gap straight;

Then cogging torque is derived by the varying air-gap permeability due to slotting. By using the concept of relative permeance \( \hat{\mu} \), the flux density of slot opening region expressed as:

\[
B_{si}(x) = \hat{\mu}(x) B_{\text{air-gap}}
\]  

As shown in Fig.2, the net cogging torque at any magnet position is calculated from the flux density in slot-opening region:

\[
T_c = \sum_{k=0}^{Q_o} L_{stk} \int_0^{b_0} \left( \frac{B_{rh1}^2 - B_{rh2}^2}{2\mu_0} \right) r \, dr
\]  

Where \( L_{stk} \) is axial stack length, \( b_0 \) is width of slot opening, \( B \) indicates flux density produced by PMs.

![Figure 1: Schematic of a SPM motor having 4-pole rotor and 6-slot stator](image1)

![Figure 2: Air-gap representation for relative permeance method in slot-opening region](image2)

![Figure 3: Side view of the axial pole-paired rotor](image3)
2.2 Proposed Axial Pole Pairing

The phase of cogging torque can be reversed as magnet pole arc changes, thus total cogging torque can be reduced by conjoining magnets having the same stack length but different pole arc [13]. In addition to magnet pole arc, stack length, proportional to magnitude of cogging torque, can be considered as design variable shown in Fig.3 (a). The principles of axial pole pairing are illustrated in Fig.3 (b). Accordingly, improved pole pairing considering axial stack length is proposed in this paper.

Therefore cogging torque is examined by altering the value of $L_{stkA}$, $L_{stkB}$ and pole arc A, B. Firstly stack length is fixed and only pole arc is varied so that cogging torque using axial pole arc pairing is examined as result. Then all the variables change for cogging torque to be compared with the precedence.

2.3 Cogging Torque Reduction Using the Axial Pole Pairing

Cogging torque characteristics by conventional pole pairing are illustrated in Fig.4. $T_{cog,pp}$ means the peak to peak value of cogging torque. The contour map presents the peak to peak value of cogging torque versus pole arc pairing of A and B, when two of rotors having the same stack length are aligned axially. From Fig.4 (a), a pair of pole arc (A, B) = (0.97, 0.8) is selected to verify the validity of axial pole arc pairing.

As shown in Fig.4 (b), cogging torque can be reduced by 71.98% as a result of by pole arc pairing. The same pole arc pair is adopted to see how axial stack length pairing affects cogging torque reduction. The optimal stack length pair of 5[mm], 11[mm] is obtained to reduce cogging torque produced by axially pole arc paired magnets.

The features of cogging torque with different pole arc and stack lengths are illustrated in Fig.5. In case of different stack length, given an example of $L_{stk A}=5$[mm] and $L_{stk B}=11$[mm], area for design is somehow different as shown in Fig.5 (a). From this, the fact that pole arc of magnet having shorter stack length yields stronger influence on cogging torque than one with longer stack length is derived. Also it is concluded that some combinations of different pole arc and stack length can be selected to yield great effect on cogging torque reduction from Fig.5 (b).

Table 1 indicates the representative models used for analysis. Normal model X is one that the pole pairing is not applied. It consists of 0.97 of magnet pole arc ration and 16 [mm] of stack length. Model Y represents the one axial pole arc pairing is applied but two of conjoined magnets have the same stack length. If a condition of different stack length is added to model Y, then it becomes model Z.

As illustrated in Fig. 6, proper pole arc and stack length pairing can reduce cogging torque. Model Y has 71.98 % of benefit compared to normal model, and model Z has 86.02 % of advantage to the normal one.
3 Conclusion

The axial pole pairing is investigated to reduce cogging torque in a 3-phase SPM brushless machine with 4-pole 6-slot configuration. By adjusting the value of pole arc and stack length, which aligned magnets consist of, cogging torque can be reduced. Thus the output characteristics of SPM motors can be improved. Reduced cogging torque is demonstrated by using an analytical method, based on space harmonic analysis. Although the investigation is undertaken based on analytical approach, it is expected that the proposed method can be validated by finite element method and applied to other PM machines with different configurations.

References


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