Torque ripple reduction in homopolar poly-phase transverse flux machine

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Abstract: The problem of high ripple in output torque is inherent to switched reluctance and permanent magnet machines compared to conventional machines. Torque ripple is undesirable as it leads to increased audible noise, speed ripple, and fatigue. Torque ripple is more prominent in complex machines like TFMs. This paper aims to tackle the problem of torque ripple in the homopolar poly-phase transverse flux permanent magnet machine by machine design approach. Rotor pole shaping, increase in number of repetitions, and increase in number of phases have been considered to reduce torque ripple. The 3-D finite element simulations have been carried out for the considered variations in geometry. Results of nature of air-gap flux density at no-load, cogging torque, average torque, and % ripple in the output torque are used to comment on the effectiveness of the torque ripple reduction techniques. The objective of this research is to reduce the torque ripple in the output torque to 10%. The technique/combination of techniques resulting in reduced torque ripple has been suggested to be implemented in the prototype.

1 Introduction

Transverse flux machines (TFM) are being explored as an alternative to radial flux machines (RFM) and axial flux machines (AFM) in various applications. The RFM and AFM either permanent magnet or switched reluctance type face the problem of high ripple in output torque leading to increased audible noise, speed ripple, and fatigue. This problem is more prominent in TFM due to their complex construction. Thus, one of the important domains of research is optimisation of TFM design for torque ripple reduction. Torque ripple in the output can be reduced by two ways, changes in machine design and using improved control techniques for the switching power devices [1, 2].

There are numerous variations in design of TFMs and hence torque ripple reduction techniques vary for each novel geometry. Method of tooth shape optimisation of rotor in case of flux concentrating geometry has been discussed in [3]. Shifting of stator poles for cogging torque reduction has been discussed in [4–6]. Use of Herringbone teeth for reduction in ripple torque in flux concentrating two-phase TFM has been suggested by Ahn and et al. in [7]. For reduction of cogging torque, optimisation of ratio of stator and rotor circumferential widths to pole pitch has been studied for a flux switching TFM in [8]. For a modulated pole TFM, tooth pitching is used for reduction of harmonics in back-EMF waveform and cogging torque in [9]. While, in [10], it has been proposed to insert aluminium barriers between the stacks of single-phase TFM to reduce mutual coupling and cogging torque. Control technique for torque ripple reduction in TFM is discussed in [11].

This paper aims to reduce the torque ripple in the output to 10% by machine design approach for a homopolar poly-phase transverse flux permanent magnet machine discussed in [12]. The topology under consideration is briefly discussed in next section. In the third section, techniques considered for reducing torque ripple have been discussed. In the fourth section, comparison of torque ripple reduction techniques is reported and the conclusion of the work is presented in fifth section.

2 Proposed topology of homopolar poly-phase transverse flux machine

The assembled structure of the proposed machine and its’ exploded view is shown in Figs. 1a and 1b, respectively. This geometry enables to obtain a poly-phase supply using a single stack of TFM. The homopolar nature of the field flux improves power factor. Using a single cylindrical magnet and rotor discs, flux concentration is achieved to obtain peak flux density of 0.8 T using a ferrite magnet with remnant flux density of 0.34 T. This is a three-phase machine with 12 stator poles, eight rotor poles both having pole arc to pole pitch ratio of 0.5 [Case (A(a))]. While analysing this geometry, it has been observed that torque ripple in the output is 92.84% which is much higher than allowable percentage of torque ripple. Fig. 2a shows waveform of cogging torque and output torque. The harmonic content of the torque output is shown in Fig. 2b. The objective of this research is to reduce the torque ripple in the output to 10%, which is usually acceptable.

3 Torque ripple reduction techniques for homopolar poly-phase transverse flux machine

The methods of torque ripple reduction considered here are rotor pole shaping, increase in number of repetitions, and increased number of phases. Three-dimensional finite element analysis (FEA) simulations have been carried out for the initial geometry and variations in the geometries considered for torque ripple reduction. The parameters considered for comparison of torque ripple reduction techniques are nature of air-gap flux density at no-load, cogging torque, average torque, and % ripple in the output torque.

3.1 Rotor pole shaping

This technique is used for obtaining sinusoidal flux density waveform in the air gap. In case of surface-mounted radial flux PM machines this achieved by shaping the magnet keeping the magnetisation pattern radial/parallel or by dividing the magnet arc in smaller pieces and magnetising it according to its’ position. In case of proposed geometry, a sinusoidal flux density pattern of the magnet field can be achieved by shaping the projections of the flux concentration discs on the rotor (rotor poles). Initially, the rotor poles are has been considered to be 180° electrical, and its’ shape is circular along the circumference of the rotor disc as shown in Fig. 3a. Five rotor pole shapes as shown in Fig. 3b have been considered for obtaining more sinusoidal flux density pattern.
3.1.1 150° magnet pole arc [case A(bi) and A(bii)]:

From Fig. 2b, it is observed that 6th harmonic is dominant in the output torque. To reduce 6th harmonic in the output torque, 5th and 7th harmonics from the spatial distribution of flux density have to be attenuated. This is usually done by modifying the pole arc length of the rotor poles in case of radial flux surface-mounted permanent magnet machines. For reducing the gth space harmonic, pole arc $\theta$ is selected using: $g \times \theta = n \times 180$; where: $n = 1, 2, 3, \ldots, (n-1)$ [13]. Using this method, two orders of harmonics cannot be simultaneously cancelled as each one would have a corresponding arc length. For, three-phase systems, 5th and 7th are the dominant space harmonics of the flux density, which corresponds to pole arc of 144° and 154.3°, respectively. Choosing pole arc of 150° would attenuate both 5th and 7th harmonics of flux density, but will not completely eliminate any. This will reduce the ripple torque [2]. Disadvantage of this method is that the mean value of torque reduces as magnitude of fundamental component of flux density is reduced.

For the geometry under consideration, 150° pole arc has been achieved by two ways. First by choosing pole arc to pole pitch ratio 5/12 (which equals to 0.4166) as shown in Fig. 3bi. Second method is to keep the pole arc by pole pitch ratio equal to 0.5 at base of rotor pole while the rotor pole surface has pole arc of 150° as shown in Fig. 3bii.

3.1.2 Vertical edges chamfered [case A(biii)]:

Cogging torque in case of surface mounted PM machines is developed due to interaction of magnet edges and stator teeth. The overall cogging torque is the sum of the forces at each of the magnet pole tips [2]. To reduce the interaction of rotor pole tips and stator pole tips in proposed geometry, the vertical edges of the rotor pole were chamfered by 7 mm at an angle of 45°. This rotor pole shape is shown in Fig. 3biii.

3.1.3 Top surface chamfered [case A(biv)]:

Shaping of permanent magnets to get more sinusoidal flux density and hence back-EMF which results in reduced ripple torque has been suggested in [2, 13, 14]. To get more sinusoidal flux density pattern, in the machine under consideration, the top surface of the projections on rotor flux concentration disc is chamfered by 5 mm at an angle of 45°. This rotor pole shape is shown in Fig. 3biv.
3.1.4 Vertical edges and top surface chamfered [case (Abv)]: Combination of above two methods (2 and 3) has been applied simultaneously in this variation. The vertical edges have been chamfered 7 mm at an angle of 45° and the top surface is chamfered 5 mm at angle of 45°. This rotor pole shape is shown in Fig. 3bv.

Fig. 4a gives the flux density pattern obtained by six different rotor pole shapes (initial and five variations). Figs. 4b and c show the cogging torque and on-load torque waveforms for the six rotor pole shapes.

3.2 Increase in number of repetitions [case (B)]

Increase in number of repetitions means increase in number of alignments and un-alignments of poles per revolution. This is achieved by increasing number of stator poles and rotor poles keeping number of phases constant. Increase in number of repetitions will reduce the step angle and hence torque ripple.

The initial design had 12 stator poles and eight rotor poles, the design is modified to have 24 stator poles and 16 rotor poles. The machine dimensions, speed, and ampere-turn rating are same for both the designs. With increase in number of repetitions, rate of change of flux is increased and hence frequency is increased. Number of turns per coil are reduced, but number of coils per phase have increased leading to same number of turns per phase, resulting in same value of induced EMF. Hence, the total output torque remains same as in initial case.

Figs. 5a and b show the comparison of cogging torque and load torque, respectively, for initial 12/8 geometry and 24/16 geometry.

3.3 Increase in number of phases [case (C)]

In literature, this method to reduce torque ripple is suggested for both switched reluctance machines (SRM) as well as permanent magnet machine. In case of SRM, increase in number of phases will increase the overlap angle between commutation of phases hence reduce torque ripple. While in case of sinusoidal PM machines fed with purely sinusoidal supply, torque only contains harmonics of angular frequency “km” with km even. If the phase number m increases, the rank of harmonics in torque waveform increases and magnitude decreases [14]. It is also suggested in literature that odd number of phases are preferred over even number of phases. The 5 and 7 phase machines are seen to give reduced torque ripple of the order of 5% to 10% [2]. The only disadvantage of this method is increase in number of legs of the inverter (cost of power electronics hardware) and complexity in drive circuit [1].

Thus, the proposed topology of the TFM has been modified to have five-phase stator. The number of projections on stator ($P_s$) and rotor ($P_r$) is related to each other by number of phases ($m$): $\text{LCM}(P_s \times P_r) = (m \times P_r)$ [15]. Keeping the number of rotor projections 8 (same as initial design), number of stator projections comes out to be 10. For the same dimension machine keeping the magnetic loading of the machine same, the results for cogging torque is shown in Fig. 6a. As the number of stator poles are reduced from 12 to 10, winding area is increased. Keeping the number of turns per coil and conductor current density constant, allowable current per coil is increased. With the new current loading, torque output is shown in Fig. 6b.
Comparative analysis of torque ripple by design variations

The design variations as discussed in section 3 are applied to the proposed geometry. Fig. 7 shows the comparison of all the variations considered on the basis of: (a) cogging torque, (b) average torque, (c) 6th harmonic component in output torque, and (d) % torque ripple. Following conclusions can be drawn from Fig. 7a–d.

1. Case A(bii) has minimum cogging torque as it is observed to have minimum flux under unaligned poles (refer Fig. 3a). This rotor pole shape gives highest average torque but also highest 6th harmonic component, hence highest torque ripple.
2. Case A(bv) has second lowest cogging torque, increased average torque and lowest % torque ripple.
3. Case B. Cogging torque is reduced by 45%. Also, torque ripple has decreased by 71% but at the cost of 1 Nm decrease in torque.
4. Case C. Cogging torque is reduced by 81%. Also, torque ripple has been decreased by 76% with 0.383 Nm decrease in average torque.

Using single torque ripple reduction technique, the aim of 10% torque ripple has not been achieved. Hence, a combination of two techniques has been tried. Out of the rotor pole shaping techniques, rotor pole having vertical edges and top surface chamfered (A(bv)) gives best results. Also, 10/8-5-phase machine (C) gives better results than 24/16-3 phase machine (B). Thus, 5-phase machine with 10 stator poles and eight rotor poles, with rotor poles modified to have vertical edges and top surface chamfered has been considered (C + A(bv)).

Figs. 8a and b show the cogging torque and on-load torque results in comparison with original geometry. Table 1 compares the results of initial (A(a)) and final geometry (C + A(bv)) on the basis of cogging torque, average torque, 6th harmonic component of torque output, and % torque ripple. It is observed that cogging torque is reduced by 84.77% and average torque is increased by 7%. The output torque of final geometry does not have a 6th harmonic component, but has 0.15 Nm and 0.08 Nm of 5th and 10th harmonic components, respectively. Ripple in the output torque is 10.6%, which is 88.58% less compared to initial geometry and near to expected and acceptable value.

4 Comparative analysis of torque ripple by design variations

5 Conclusion

Rotor pole shaping, increase in number of repetitions, and increase in number of phases are the three techniques studied to reduce ripple in output torque of initially designed homopolar poly-phase TFM. Six rotor pole shapes have been compared on the basis of cogging torque, average torque, 6th harmonic component, and % ripple in output torque. The rotor pole with vertical edges and top surface chamfered gives better results than other variations. Increasing number of phases of the machines gives better results than increase in number of repetitions in terms of reduction in cogging torque, increase in average torque and reduction in ripple torque.

A 5-phase machine with 10 stator poles and eight rotor poles having vertical edges and top surface chamfered results in 10.6% of torque ripple. This value of ripple in torque output is near to acceptable value of 10%. Shaping of rotor poles in the discussed geometry is much easier than shaping the magnets in case of surface-mounted PM machines. The property of the machine being single stack poly-phase TFM is used for reducing the torque ripple.
Both the methods for reducing torque ripple do not increase the complexity of the original machine and are easily implementable in the prototype.

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7 References

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