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TORQUE PERFORMANCE OF AXIAL FLUX PERMANENT MAGNET FRACTIONAL OPEN SLOT MACHINE WITH UNEQUAL TEETH

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Abstract. Torque ripple in electrical machines is generally considered as an undesirable effect as it results with rough operation, vibration and noise. This paper looks into torque ripple minimization of fractional open slot axial flux permanent magnet machines by employing an optimization procedure; particularly interest is paid to a single-layer machine with unequal teeth. Evaluation between the single-layer machine and its double-layer counterpart is highlighted, and the results show attractive performance of the single-layer machine with unequal teeth over its double-layer counterpart.

1. INTRODUCTION

Fractional slot permanent magnet (PM) machines are currently receiving increased attention for electric vehicle applications. This is mainly attributed to their potential advantages in improved manufacturability, cost reduction and good performance. Amongst others, axial flux topologies with single-layer (SL) fractional open-slot windings are of particular interest as they are ideal options for pre-formed modular coils and of reduced ripple torque in some pole/slot combinations [1-4]. Certain PM machines with regular slot SL fractional windings also show higher torque capacity than their double-layer (DL) counterpart [5-7]. The torque quality (ripple) of the former compares favourably to the latter when driven with trapezoidal wave currents, but with sinusoidal currents the effect is opposite [5]. Therefore this paper looks to investigate the possibility to improve the torque quality of SL machines with sinusoidal current excitation.

To further enhance the torque performance of the SL PM machines, novel topologies of SL fractional slot machines with unequal teeth have been introduced in [8]. By the addition of unequal teeth, the slots become irregularly distributed and the winding factor in SL machines becomes adjustable, allowing for enhancement of the winding factor, an aspect not possible with DL machines. The typical method is to increase the tooth width around which the coil is wound and decrease width of the remaining teeth as shown by Fig. 1(a) becoming Fig. 8. By this adaptation, the coil can link higher magnetic flux and better magnetic exploitation is achieved [9]. Nearly all the work done in this regard [8-12] is applied for trapezoidal wave currents, whereby the winding factor is fully maximised leading higher torque capacity and quality when compared to DL machines. In [11] and [12] a similar occurrence of increased capacity and inferior quality as in [5] is reported when these topologies are driven with sinusoidal currents. Additionally the works [8-12] deal with radial flux structures with semi-enclosed slots, and the effects of the magnet pitch are not treated for except in [10]. In [2], open-slot axial flux machines are presented with unequal teeth; the

machines presented are also driven by trapezoidal currents and are modelled as radial flux structures. Of all the works done none dealt with FE-coupled optimization of machine parameters with the main objective of torque quality improvement.

This work aims to objectively improve torque quality in open-slot axial flux PM machines driven by sinusoidal currents, by full FE-coupled optimization of the main machine parameters affecting torque. The work involves comparative analysis of a SL and DL machine, in which both are optimized objectively for torque ripple minimization.

2. MACHINE TOPOLOGIES

Fig. 1 shows linearized 2D models of two fractional open slot (30-pole/36-slot) axial flux permanent magnet machines, in which (a) is of single-layer topology while (b) is of double-layer topology. The 30-pole/36-slot combinations are popular due to their high fundamental winding factors, high lowest common multiples, and high greatest common divisors. The machines were previously optimized for maximum torque density under sinusoidal excitation and will be used as base machines. Design data of the machines is presented in Table 1.

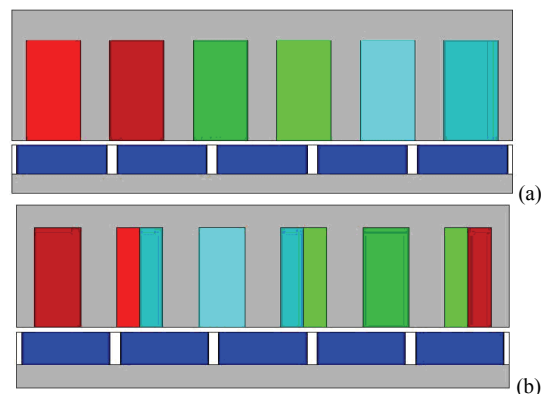


Fig. 1: Base machine models; (a) single-layer with equal teeth, and (b) double-layer.

Table 1: Design Data of Base Machines

	Single Layer	Double Layer
Stator outer diameter, mm	330	330
Total axial length, mm	55	55
Diameter Ratio	0.619	0.652
Magnet arc to pitch ratio, r_f	0.915	0.9
Slot to teeth width ratio, k_d	0.653	0.563
Teeth width ratio, c_p	1	1

3. TORQUE RIPPLE MINIMIZATIONS

3.1 Finite Element Modeling

The axial flux machines are modelled as linearized 2D structures with negative boundary conditions and an air-gap element as shown in Fig. 1. The torque performances of these machines are calculated by both the Maxwell stress tensor and virtual work methods given by:

$$T = \frac{pr_{avg}^2 L}{\mu_0} \int_{\theta_1}^{\theta_2} B_r B_\theta d\theta \quad (1)$$

$$T_{vw} = \frac{dW'}{ds} \cdot r_{avg} \approx \frac{\Delta W'}{\Delta s} \cdot r_{avg} \quad (2)$$

where p is the pole pairs, r_{avg} the average air-gap radius, L the machine axial length, B_r and B_θ the flux density components from the macro air-gap element, W' is the magnetic co-energy, and s some small displacement.

To validate the accuracy of the FEM torque calculation, a double-layer 30-pole/27-slot AFPM machine shown in Fig. 2 has been modeled [13]. The measured and calculated torque versus current ($i_d=0$) characteristics are compared in Fig. 3. It is evident that both results correlate well with each other.

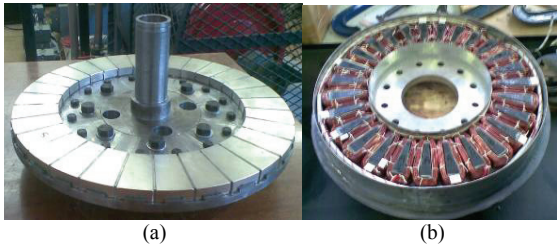


Fig. 2: Single-sided AFPM machine with double-layer fractional open slot winding, (a) rotor and (b) stator.

The instantaneous torque waveforms of two base machines of Fig. 1 are shown in Fig. 4(a). The instantaneous torque of the single-layer machine, calculated by the two FE methods, is shown in Fig. 4(b), and the results agree well with only about 0.3 % difference.

From the initial instantaneous torque waveforms of the base machines presented, in Fig. 4(a) it is evident that the single-layer machine has higher torque capability but with higher ripple content than the double-layer machine in agreement with [5], [11-12], [14].

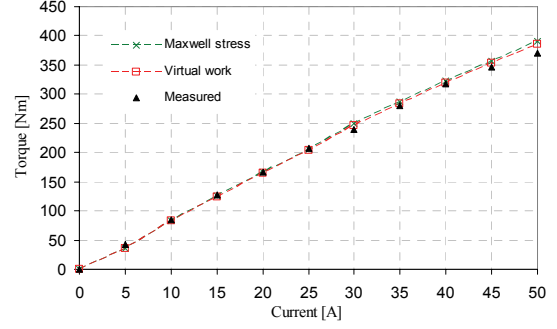


Fig. 3: Torque of the AFPM machine at different armature currents.

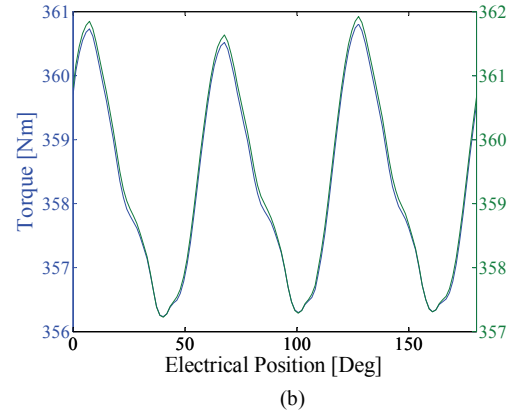
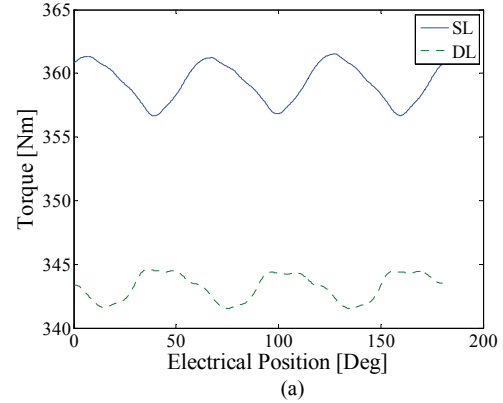


Fig. 4: Instantaneous torque waveforms, (a) single and double layer machines, (b) Maxwell stress tensor and co-energy method (co-energy approximately 1 Nm less) for single-layer winding.

3.2 Optimization for Minimum Torque Ripple

a) Parameters affecting torque ripple

In the two base machines, the parameters chosen to investigate torque ripple are the magnet arc to pitch ratio r_f , slot to teeth width ratio k_d and the teeth width ratio c_p as shown in Fig. 5, as follows:

$$r_f = \frac{\text{PM pole}}{\text{pole pitch}};$$

$$k_d = \frac{\text{slot width}}{\text{tooth pitch} - \text{slot width}};$$

$$c_p = \frac{\text{inner tooth width}}{\text{outer tooth width}} \quad (\text{applicable only to SL machine}).$$

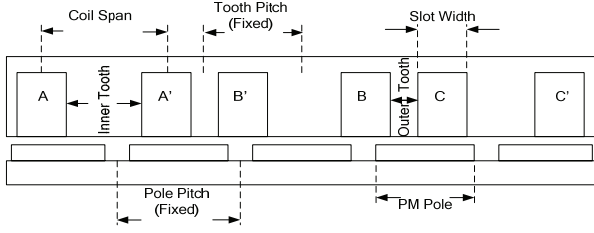


Fig. 5: Representation section of single layer PM machine with unequal teeth.

b) Optimization procedure

The optimization procedure involves first the definition of the objective function for the optimizations, which is given by,

$$F = y_{par} - \sum_{i=1}^n w_i \varepsilon_i, \quad (3)$$

where y_{par} is the parameter to be maximised / minimised, (in this case to minimize the peak to peak ripple, $y_{par} = T_{ave} / ripple_{p-p}$), ε_i the penalty functions, and w_i the respective weighting factors.

The penalty functions are added to the objective function in order not to violate the limits of secondary functions. The optimizations involve variation of the machine parameters given in section 3.2(a), while all other machine parameters are kept constant. Peak to peak ripple is obtained by capturing the peaks as the machine is rotated over 60° electrical (due to symmetry). Due to the machines having different torque capabilities at each case, for fair basis of comparison, torque ripple results are shown on a per unit system, based on the average machine torque at each case. The subsequent flow charts in Fig. 6 illustrate the methods. The first method uses a graphical approach while in the second method the Powell's optimization algorithm is applied.

4. RESULTS

4.1 Double layer machine: Effects of magnet pitch and slot width

As double-layer topologies cannot use unequal teeth, the optimization parameters are limited to only two. The graphical method of Fig. 6(a) was applied to obtain the surface plots shown in Fig. 7. The points of minimum torque ripple and maximum torque are presented in Table 2.

4.2 Single Layer: Magnet pitch, slot width and unequal teeth

For this topology with equal teeth the winding factor is limited to 0.966, but by using unequal teeth, winding factors up to unity can be obtained. The FE optimization method used in this section involves the method of Fig. 6(b). Fig. 8 shows the machine model with unequal teeth, and Table 2 gives the optimization results.

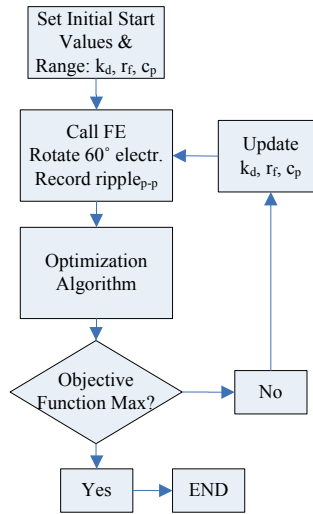
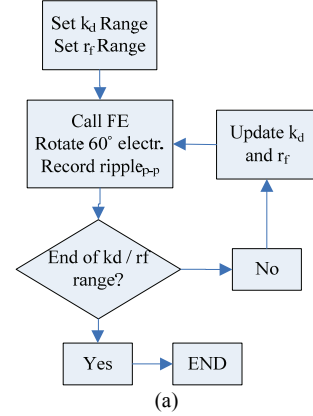


Fig. 6: Flow charts of design technique for (a) double-layer machine, and (b) single-layer machine

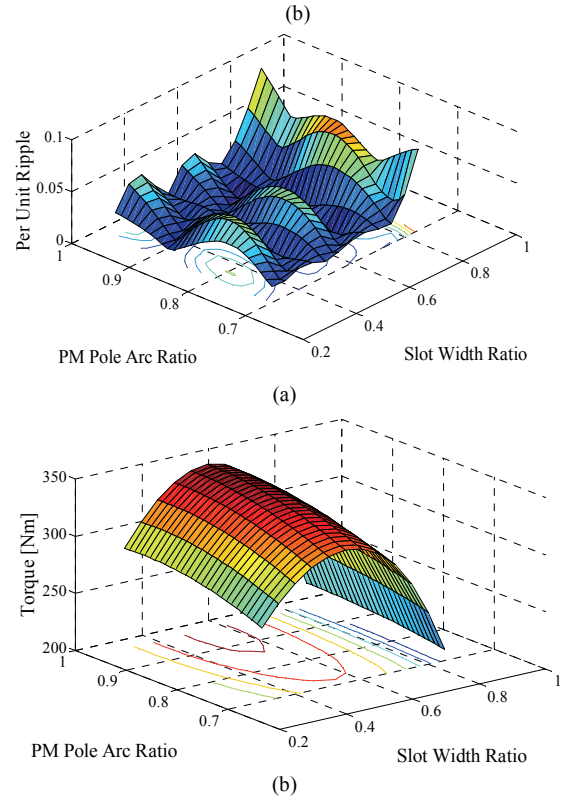


Fig. 7: (a) Peak to peak ripple and (b) average torque of double-layer machine.

Table 2: Optimization results based on the same copper losses

	k_d	r_f	c_p	Winding Factor	Torque [Nm]	Per Unit Ripple
SL Base	0.653	0.915	1	0.966 (fixed)	359	0.01392
SL Min Ripple	0.653	0.91	1.02	0.968	362	0.00193
SL Max Torque	0.555	0.93	1.16	0.986	377	0.03527
DL Base	0.563	0.9	1	0.945 (fixed)	343	0.00728
DL Min Ripple	0.65	0.92	1	0.945 (fixed)	332	0.00517
DL Max Torque	0.55	0.96	1	0.945 (fixed)	354	0.03463

As can be seen from the results, by adjusting the teeth ratio c_p , a higher winding factor is obtainable for SL machines (Table 2). With the SL machine optimized for minimum ripple, the torque only slightly increases but there is a good 84% reduction in torque ripple compared to the base machine with equal teeth. For the DL machine, there is also good reduction in ripple content of 42% compared to the base machine, but with this a loss in average torque of 3.3%. In Fig. 9, the torque waveforms of the two machines before and after being optimized are presented to show the optimization development made.

Further optimizations of the base machines were done but instead for maximum torque capability. The results are given in Table 2 and show in both cases an increased torque capability but with poor torque quality.

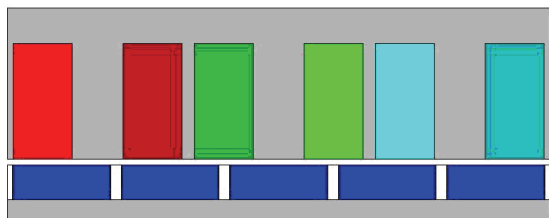


Fig. 8: Linear model of SL machine with unequal teeth

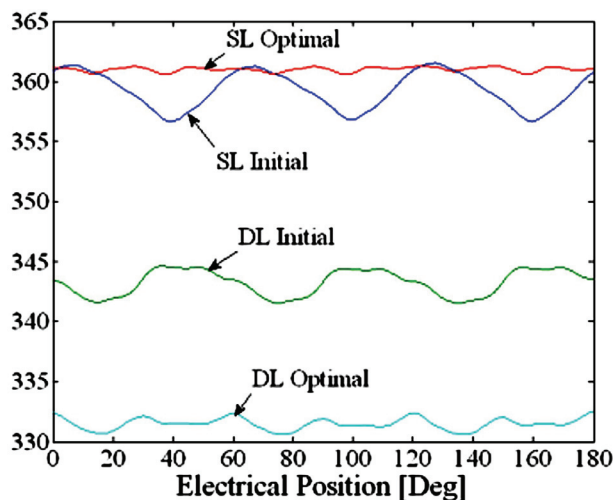


Fig. 9: Instantaneous torque waveforms of SL and DL machines before and after being optimized for minimum torque ripple

5. CONCLUSION

By full FE-coupled optimization of the main machine parameters that affect torque performance, the problem of improved torque capacity but with reduced torque quality of SL machines with sinusoidal currents could be eliminated. The results show that both the torque capacity and torque quality of the sinusoidal driven SL machine compares favorably over its DL counterpart.

This paper also presents an alternative method to either enhance torque capability or minimize torque ripple in open slot single-layer PM machines by using unequal teeth. It shows that the torque ripple in sinusoidal machines can be significantly reduced by incorporating unequal teeth.

It should be noted that the manufacturability for unequal teeth SL machines may seem to be not as good as initial equal teeth one, however, the manufacturing costs are not necessarily more expensive. This is because the manufacturing process is practically the same once a dedicated rolling and punching process is set up.

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