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# Torque Performance of Axial Flux PM Fractional Open Slot Machine with Unequal Teeth

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## Abstract

*Cogging torque ripple and torque ripple in electrical machines are generally considered as undesirable effects and results in rough operation, vibration and noise. This paper looks into minimization of these parasitic effects in axial flux permanent magnet machines with fractional open slots by employing a finite element coupled 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.*

## I. INTRODUCTION

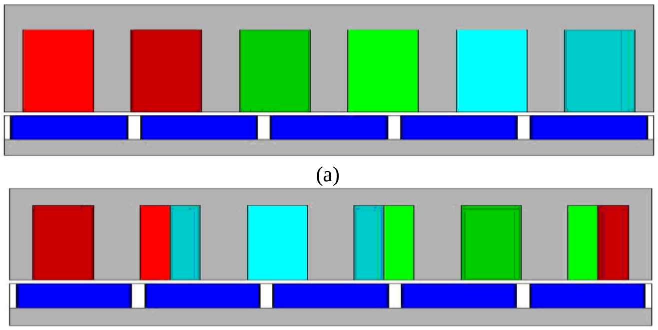
FRACTIONAL slot permanent magnet (PM) machines are currently receiving increased attention for wind and electric vehicle applications. This is mainly attributed to their potential advantages in improved manufacturability, cost reduction and high power density levels over conventional radial flux machines. 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 non-overlap modular coils. In certain pole/slot combinations, open slots show reduced ripple [1-4]. Certain PM machines with regular slot SL fractional windings show higher torque capacity than their double-layer (DL) counterpart [5-7]. The torque 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 under 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 structures. 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 adapting Fig. 1a to 6. 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 but with 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], an open-slot axial flux machine is presented with unequal teeth, but the machine presented is driven by trapezoidal currents and is modelled as a radial flux structure. Of all the works found, none specifically deal with particular optimization of machine parameters for the objective analysis of torque quality.

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 machine parameters affecting torque. The work involves comparative analysis of a SL and DL machine, in which both are optimized objectively for torque quality.

## II. MACHINE TOPOLOGIES

Fig. 1 shows the sectional layout 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 (LCM), and high greatest common divisors (GCD). The machines were previously optimized separately for maximum torque density under sinusoidal excitation. Data of the machines is presented in Table 1.


(a)

(b)

**Fig. 1. Base machine 1 and 2 models; (a) Single-layer with equal teeth, and (b) Double-layer.**

By initially optimizing each machine separately, leading to two base machines, each topology is in its optimum before the analysis. This provides a fair base upon which to begin from, as compared to using one base machine which holds either a SL or DL winding; as the dimensions of a single base machine could be more suited to one winding type over the other.

TABLE I
DESIGN DATA OF TWO BASE MACHINES

| | Single Layer | Double Layer |
|---|---|---|
| Stator outer diameter | 330.0 mm | 330 mm |
| Total axial length | 55 mm | 55 mm |
| Diameter Ratio | 0.619 | 0.652 |
| Magnet arc to pitch ratio | 0.915 | 0.9 |
| Slot to teeth width ratio | 0.653 | 0.563 |
| Teeth width ratio | 1 | 1 |
| Power Density | 4366.39 kW/m$^3$ | 6343.55 kW/m$^3$ |
| Average Torque | 361 Nm | 334 Nm |
| Per Unit p-p Cogging | | |
| Per Unit p-p Ripple | | |

## III. TORQUE ANALYSIS

### A. Finite Element Modeling

The cross sections of axial flux machines are not the same across their stack length and present no 2D symmetry as radial flux machines do, thus the full 3D modelling. The downside to full 3D modelling is heavy computational time required. To simplify this, axial flux machines can be modelled as 2D linear structures as in Fig. 1, normally based upon their average radius *dr* as in Fig. 2. This approach is suitable for solving most issues but when dealing with instantaneous torque profiling, more precision is required. To overcome this and avoid full 3D modelling, an alternative approach, adopted in this paper is multi-slice or quasi 3D modelling. The method involves modelling several linear 2D models, based on several diameter lengths along the machine stack, and taking the average of these.

The axial flux machines in this paper are modelled as 1/6th sections 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

$$T = \frac{p r_{avg}^{2} L}{\mu_0}\int_{\theta_1}^{\theta_2} B_r B_\theta \, d\theta \quad \text{and}$$

$$T_{VW} = \frac{dW'}{ds}\cdot r_{avg} \approx \frac{\Delta W'}{\Delta s}\cdot r_{avg} ,$$

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

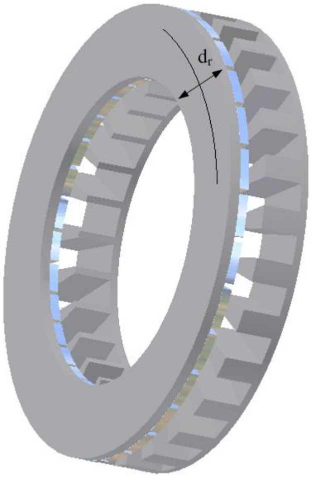
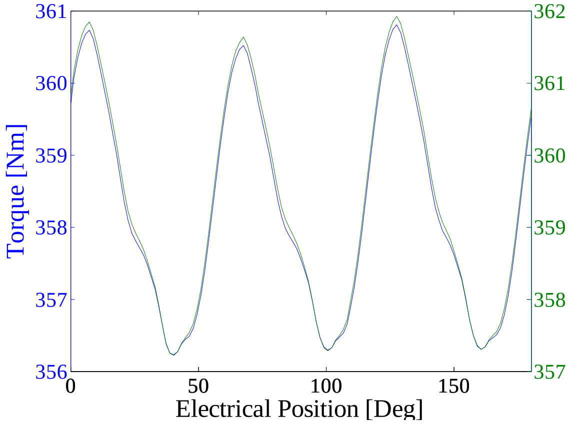


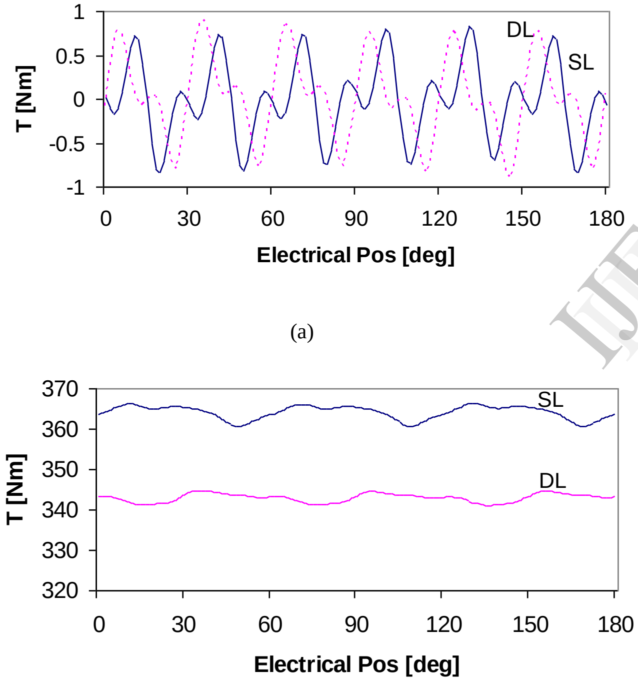
**Fig. 2. Axial flux machine.**

The instantaneous torque of machine 1, calculated by the two methods is shown in Fig. 2, and the results agree well with only about 0.3 % in difference.



(b)

**Fig. 3. Maxwell stress tensor and co-energy method (co-energy approximately 1 Nm less)**



(a)

(b)

**Fig. 4. Instantaneous torque waveforms of the two base machines, a) cogging torques, b) torque ripple.**

From the initial instantaneous torque waveforms of the machines, Fig. 4, the single-layer machine has per unit cogging torque. The single layer machine also possesses higher torque capability (5.74%), but with higher per unit ripple content than the double-layer machine as is found in [5], [11-12].

## B. Optimization for Torque Quality

In the two machines, the parameters principally affecting the torque ripple are found to be, as shown in Fig. 3 the (i) Magnet arc to pole pitch ratio $r_f$, (ii) Slot to teeth width ratio $k_d$ (inner+outer teeth), and (iii) Inner to outer tooth width ratio $c_p$, (applicable only to single layer machines).

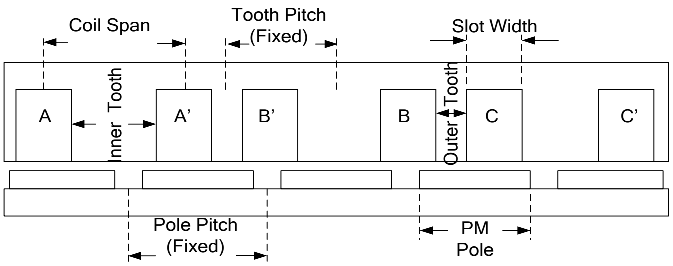


**Fig. 5. Representation section of single layer pm machine with unequal teeth.**

### *Optimization Procedure*

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

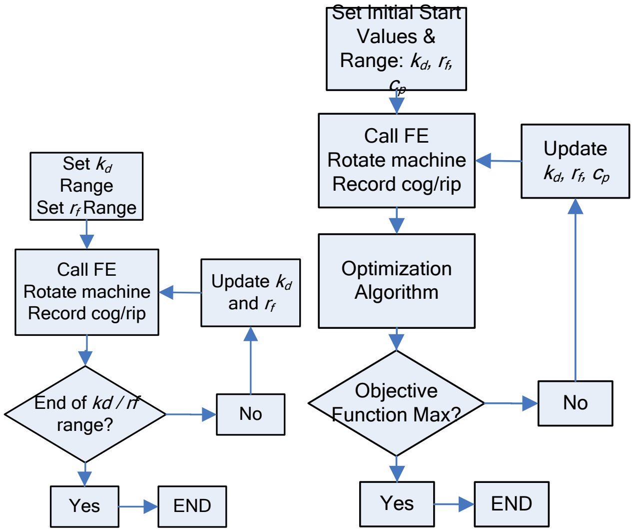
$$F = y_{par} - \sum_{i=1}^{n} w_i \varepsilon_i ,$$

where ypar is the value to be maximised, in this work three main objectives are persued which are T/cogging$_{p\text{-}p}$ , T/ripple$_{p\text{-}p}$ and T. Penalty factors $\varepsilon_i$ and their respective weighting factors $w_i$ are also included, so as the objective function does not to violate the limits of secondary functions. The optimization algorithm then varies the selected machine parameters hunting for a maximum, while all other machine parameters are kept constant. Due to the machines having different torque capabilities at each case, for fair basis of comparison, torque results are compared on a per unit system based on the average machine torque in each case. The subsequent flow charts in Fig. 6 illustrate the methods employed, for the DL machine a linear search was done and for the SL machines the Powell's optimization algorithm used.

## IV. RESULTS

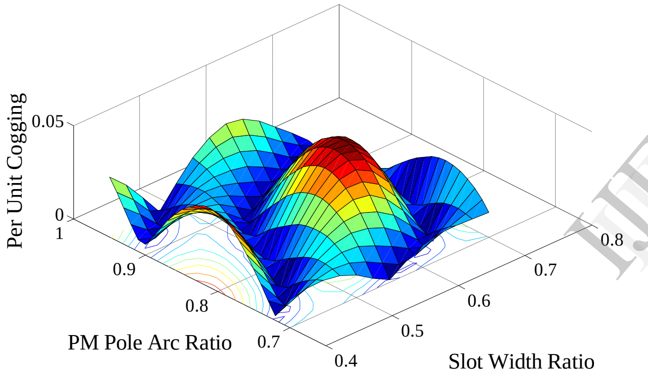
### *A. Double Layer Machine: Magnet pitch and slot width*

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

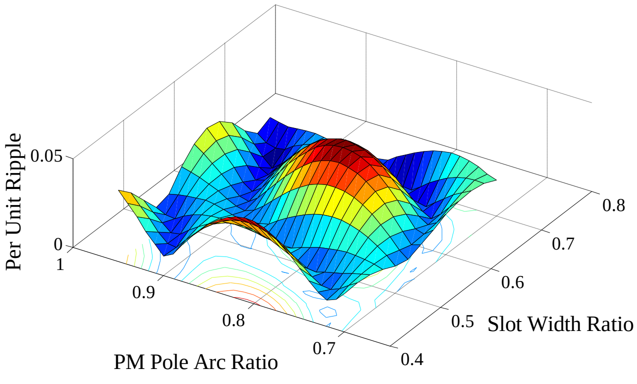


(a) (b)

**Fig. 6. Flow charts of design technique for a) Double-layer machine b) Single-layer machine**



(a)



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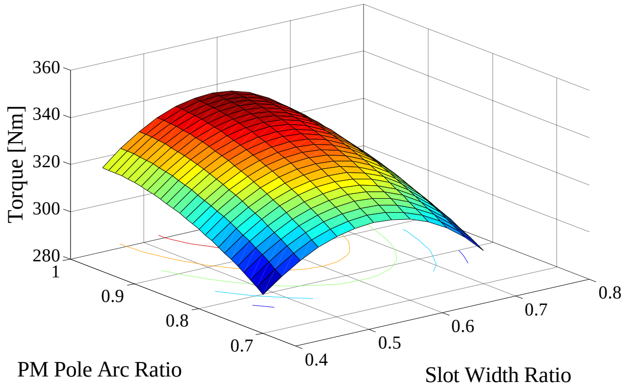


(c)

**Fig. 7. Surface plot for double layer machine a) peak to peak cogging torque b) peak to peak torque ripple c) average torque.**

### *B. Single Layer: Magnet pitch, slot width, and unequal teeth*

In a SL 30 pole, 36 slot machine with equal teeth the winding factor is limited to 0.966, but by introducing unequal teeth, winding factors up to unity can be obtained. For the torque quality investigation of this machine, the method of Fig. 4b was used. Fig. 6 shows the machine model with unequal teeth, and Table 2 the optimization result.

TABLE II
OPTIMIZATION RESULTS

| | | Slot Width Ratio | PM Pole Arc Ratio | Teeth Ratio | Winding Factor | Torque | Per Unit p-p Cogging | Per Unit p-p Ripple |
|---|---|---|---|---|---|---|---|---|
| PM 1 | DL Min Cogging | 0.45 | 0.76 | 0.5 | 0.945 | 318.5 | 0.1 | 1.33 |
| | DL Min Ripple | 0.65 | 0.92 | 0.5 | 0.945 | 331.7 | 0.12 | 0.33 |
| | DL Max Torque | 0.55 | 0.95 | 0.5 | 0.945 | 345 | 2.9 | 3.36 |
| | | | | | | | | |
| PM 2 | SL Min Cogging | 0.623 | 0.91 | 0.5 | 0.966 | 364 | 0.31 | 1.3 |
| | SL Min Ripple | 0.65 | 0.91 | 0.5 | 0.966 | 359.5 | 0.64 | 0.77 |
| | SL Max Torque | 0.562 | 0.915 | 0.5 | 0.966 | 368.7 | 1.4 | 2.6 |
| | | | | | | | | |
| PM 3 | SLu Min Cogging | 0.623 | 0.91 | 0.5 | 0.966 | 364 | 0.31 | 1.3 |
| | SLu Min Ripple | 0.653 | 0.91 | 0.508 | 0.9677 | 359.7 | 1.05 | 0.44 |
| | SLu Max Torque | 0.555 | 0.93 | 0.583 | 0.9864 | 377 | 5.11 | 3.84 |

As can be seen from the results, by adjusting the teeth ratio, a higher winding factor is obtainable for SL machines. From the results, minimum cogging torque is obtained by the DL machines, but suffers with a low average torque for this case. The SL machines have the same level of cogging as in both cases the optimization algorithm finds the same point, and it can be noted that unequal teeth provide no advantages for cogging torque reduction in this case.

In terms of torque ripple, the DL machine presents the smoothest case, but again with a low average torque. The single layer machine with unequal teeth is not too far off and has a much higher average torque.

For case of maximum torque, the single layer machine with unequal teeth is best, but with very poor torque quality.

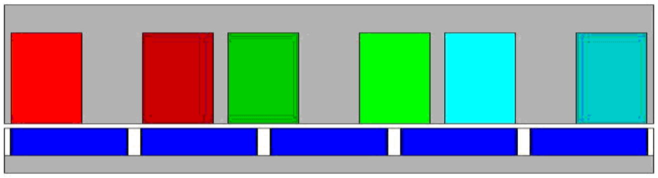
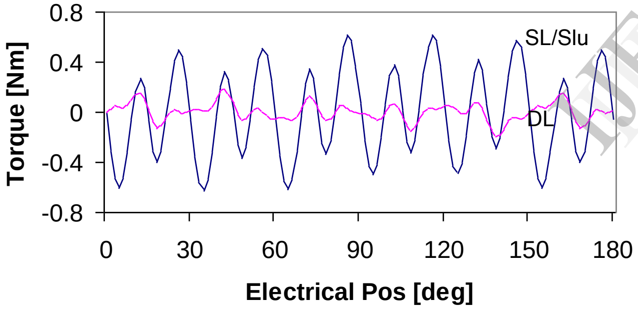
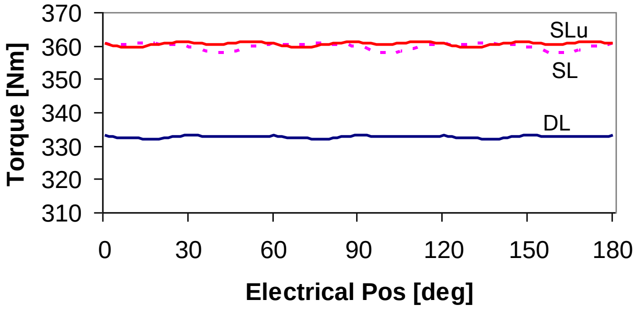


**Fig. 8. Linear model of single layer machine with unequal teeth**



(a)



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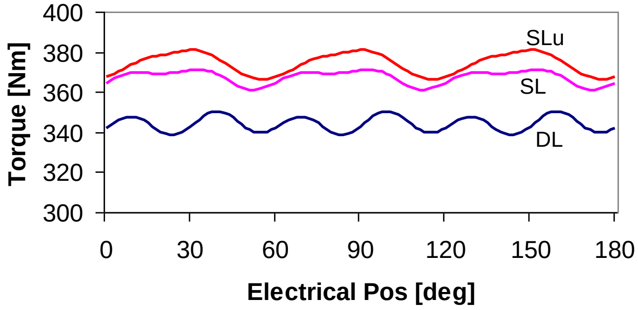

(c)

**Fig. 9. Instantaneous torque waveforms for the three machines a) minimum cogging torque, b) minimum torque ripple, c) maximum torque.**

## V. CONCLUSIONS

By full FE-coupled optimization for torque quality, it can be noted that ultimately in this topology, DL machines provide the best torque quality, but suffer from lower torque capacity. Interestingly found is the advantages of using unequal teeth for single layer machines over conventional SL machines. By employing unequal teeth, torque ripple can be minimized and torque capability increased. In terms of cogging torque though, unequal teeth present no advantages.

## REFERENCES

[1] P. Salminen, J. Pyrhönen, F. Libert and J. Soulard, “Torque Ripple of Permanent Magnet Machines with Concentrated Windings,” ISEF, Spain, Sept. 2005.

[2] R. Neji, S. Tounsi and F. Sellami, “Contribution to the definition of a permanent magnet motor with reduced production cost for the electric vehicle propulsion,” Euro. Trans. Electr. Power, 16: 437-460, 2006.

[3] A. Rix, M. Kamper, R. Wang, “Torque Ripple and Flux Density Variation Due to Stator Slot Opening of Concentrated Coil Permanent Magnet Machine,” SAUPEC Conference, Cape Town, 2007.

[4] P. Salminen, M. Niemelä, J. Pyrhönen and J. Mantere, “High-Torque Low-Ripple Fractional-Slot PM-Motors,” Proceedings of IEEE IEMDC, pp.144 – 148, May 2005.

[5] D. Ishak, Z. Q. Shu and D. Howe, “Comparison of PM Brushless Motors, Having Either All Teeth or Alternate Teeth Wound,” IEEE Trans-EC 21(1): 95-103, Mar. 2006.

[6] J. Colton, D. Patterson, J. Hudgins, “Design of a Low-Cost and Efficient Integrated Starter-Alternator,” Proceedings of IET-PEMD, pp.357 – 361, April 2008.

[7] N. Bianchi, S. Bolognani, M. Dai Pre and G. Grezzani, “Design Considerations for Fractional-Slot Winding Configurations

of Synchronous Machines," IEEE Trans-IA 42(4):997-1006, Jul./Aug. 2006.

[8] J. Cros and P. Viarouge, "Synthesis of High Performance PM Motors with Concentrated Windings," IEEE Trans-EC 17(2): 248-253, June 2002.

[9] N. Bianchi, M. Dai Pre, L. Alberti and E. Fornasiero, Theory and design of fractional slot PM machines, IEEE-IAS Tutorial Course notes, 2007.

[10] J. Cros, P. Viarouge, C. Gelinas, "Design of PM Brushless Motors Using Iron-Resin Composites for Automotive Applications," IEEE-IAS Conference, vol.1, pp. 5-11, 1998.

[11] Th. Koch and A. Binder, "Permanent Magnet Machines with Fractional Slot Windings for Electric Traction," Proceedings of. ICEM 2002, Belgium.

[12] D. Ishak, Z. Q. Zhu and D. Howe, "Permanent-Magnet Brushless Machines with Unequal Tooth Widths and Similar Slot Pole Numbers," IEEE Trans-IA 41(2): 584-590, Mar./Apr. 2005.