Nigerian Journal of Technology (NIJOTECH)
Vol. 36, No. 4, October 2017, pp. **1150 – 1154**
Copyright© Faculty of Engineering, University of Nigeria, Nsukka,
Print ISSN: 0331-8443, Electronic ISSN: 2467-8821
www.nijotech.com
http://dx.doi.org/10.4314/njt.v36i4.22

THE IMPACT OF MACHINE GEOMETRIES ON THE AVERAGE TORQUE OF DUAL-STATOR PERMANENT MAGNET MACHINES

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ABSTRACT

The influence of leading design parameters such as rotor radial size and arc lengths, aspect ratio, stator yoke thickness, stator tooth-width and slot-opening/slot pitch-ratio etc. on the average torque of permanent magnet (PM) machines having dual-stator arrangement is investigated in this study. Further, the effect of their different rotor pole numbers is also presented and quantitatively compared. The analyzed machines are optimized using the evolutionary approach with a goal for optimum torque yield. The analysis shows that, each of the varied machine parameters has an optimum value for maximum torque production owing to their varying electromagnetic reaction which tends to saturate at some point on the magnetic path. Moreover, the best performance amongst the investigated machines is given by the machine type having eleven rotor pole number.

Keywords: *average torque, dual start, machine geometry, optimal value, PM machines*

1. INTRODUCTION

The influence of machine design parameters on the overall performance of electric machines cannot be over-emphasized. This is because the output torque, power and hence efficiency of the machine ultimately depends on its optimal geometries. Thus, we have devoted this work to the impact of these design parameters which includes: the split-ratio, slot opening, stator back-iron thickness, stator tooth-width, and rotor radial size, etc. on the average torque of double-stator PM machines. An improved efficiency and torque-density design of dual rotor PM machine is proposed in [1]; it is noted that, machines having toroidal windings could deliver higher output torque and better efficiency than their counterparts equipped with traditional winding topologies. Similarly, a double-stator PM machine capable of producing large torque is realized in [2], by adopting the optimal split-ratio of the machine. Further, other design parameters such as permanent magnet length, back-iron size etc. were obtained by optimal sizing equations and also seen to contribute to the performance of the machine.

In order to predict the electromagnetic performance of synchronous PM machines, fast analytical optimization techniques with high accuracy compared to finite element analysis is adopted in [3]. The investigation in [3] also revealed that, design parameters such as the rotor pole arc, tooth width and slot-opening could have great impact on the output of the given machine. Moreover, it is proven in [4] that, by utilizing an optimal rotor yoke size, significant amount of losses could be reduced through the reduction of the machine's magnetomotive force (MMF) sub-harmonic contents. The implication being, an improved overall machine efficiency. Similarly, as demonstrated in [5], by introducing flux barriers in the stator yoke design of PM machines having non-overlapping concentrated windings, large percentage of its MMF sub-harmonics are minimized or more even eliminated completely. Consequently, it will lead to significant reduction of core and PM eddy current losses; and thus, enhance the machine's efficiency.

An integrated machine suitable for direct-drive applications, since it could produce high torque at low speed is proposed in [6]. The proposed double-stator machine in [6] combines the features of both magnetic gear (gearing effect) and that of conventional PM machine into one device. Similarly, double-stator magnetically-geared machine capable of producing larger torque density compared to traditional PM machines is proposed and validated in [7]. Optimal design parameter of the machine is obtained by finite element algorithm method.

The developed machine in this paper which is depicted

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in Figure 1, has the same number of independent parts with that proposed in [7], however, with huge structural differences, especially in the arrangement of PMs and total number of rotor(s) and stator(s). It should be noted that, the analysed machine in this study is devoid of permanent magnets in its outer stator. Moreover, the inner stator of the developed machine in this work is furnished with spoke-type of well situated permanent magnets for effective flux-focusing; this advantage is not obtainable when compared to surface-mounted permanent magnet machines (SPMs) that are mechanically weak and unstable.

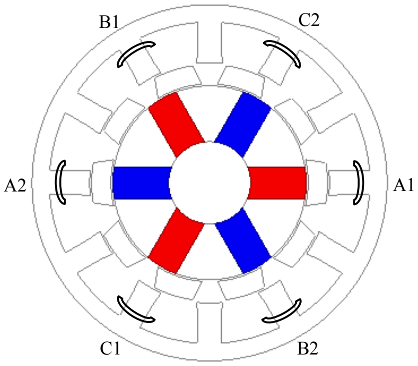


Figure 1: Structural view of the developed dual-stator 10-pole machine.

A new design of doubly-salient machine having stator-mounted PMs is introduced in [8], such that the proposed A-shaped stator machine could reduce the cogging torque in addition to its good thermal dissipation capacity. The stator structure, eventually helps to reduce the demagnetization effects on the machine. The employed leading design parameters in [8], were optimized with the objective to minimize the torque ripple while maximizing the output electromagnetic torque.

Overall, the influence of machine parameters on the average torque of double-stator PM machine having different rotor numbers is investigated and compared in this paper.

2. METHODOLOGY

The analysed machine has an active stack length of 25mm, outer-stator diameter of 90mm and 5mm air-gap length. Two-dimensional finite element analysis (2D-FEA) is used in predicting the entire results in this work. It is worth mentioning that, the investigated machine having different rotor pole numbers are optimized separately using the genetic algorithm optimization technique at a fixed copper loss of 30W. The satisfied optimization condition at fixed copper loss and constant packing factor which is taken as 0.6 in this study is expressed in equation (1), according to [9] such that the phase number of turns is directly proportional to the available slot area which is also dependent upon the split-ratio of the machine.

$$\frac{I_a^2 N_a^2}{A_a} = constant \qquad (1)$$

where I_a = per phase rms current, N_a =the number of turns per phase and A_a is the phase slot area.

The phase resistance of the machine is given in equations (2) and (3):

$$R_a = \frac{\rho_{cu} 2nN_t(L_{axial} + L_{end})}{A_a k_{pf} \big/ N_t} \qquad (2)$$

$$R_a = \frac{2n\rho_{cu} N_t^2 (L_{axial} + L_{end})}{A_a k_{pf}} \qquad (3)$$

where ρ_{cu} = copper resistivity, K_{pf} = packing factor or fill factor, N_t = number of turns per coil, L_{axial} = active stack length, n is the number of coils per phase and L_{end} = end winding length [10].

However, in this study we neglected the end winding effect, since the calculations were performed on 2D-FEA model. Thus, the copper loss Cu_{loss} is given in equation (4):

$$Cu_{loss} = 3I_a^2 R_a = \frac{6I_a^2 \rho_{cu} n N_t^2 L_{axial}}{A_a k_{pf}} \qquad (4)$$

Table 1: Parameters of the investigated machine

Item	Value							
Rotor pole number, N_r	4	5	7	8	10	11	13	14
No. of outer stator slots, N_s	12							
No. of inner stator slots, P_s	6							
Number of phases, m	3							
Phase resistance, R_a (Ω)	0.03							
Number of turns/phase, N_a	72							
Copper loss (W)	30							
Copper resistivity, ρ_{cu}(Ωm)	1.68e-8							
Packing factor, K_{pf}	0.6							
No. of turns/coil, N_t	36							

Item	Value							
Coils/phase, n	2							
Outer stator diameter (mm)	90							
Airgap length(mm)	0.5							
Active stack length, L_{axial} (mm)	25							
Aspect ratio or Split ratio	0.66	0.68	0.71	0.68	0.67	0.68	0.70	0.71
Slot opening/slot pitch ratio	0.53	0.40	0.42	0.53	0.60	0.64	0.58	0.55
Rotor radial thickness (mm)	5.66	5.48	6.03	5.68	4.91	4.15	4.18	3.84
PM thickness (mm)	9.68	7.95	7.92	9.32	8.15	7.82	8.40	8.13
Outer rotor iron width/pitch ratio	0.59	0.67	0.64	0.64	0.54	0.64	0.66	0.71
Inner rotor iron width/pitch ratio	0.53	0.47	0.46	0.49	0.75	0.63	0.69	0.57
Stator back-iron thickness (mm)	4.46	4.61	4.49	4.11	4.37	4.64	4.93	5.10
Stator tooth width (mm)	3.12	4.11	5.64	5.86	5.91	4.55	3.69	3.01

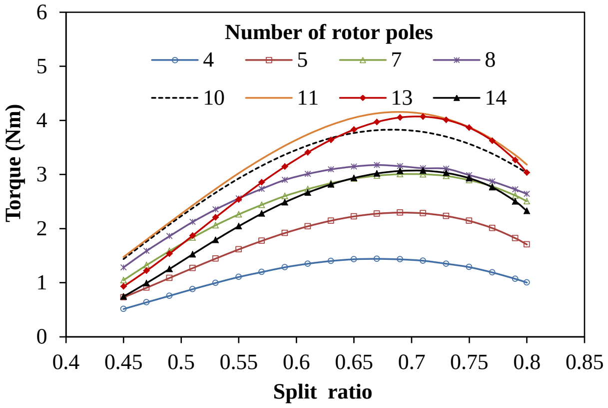


Figure 2: Variation of average torque with split ratio, i_d=0.

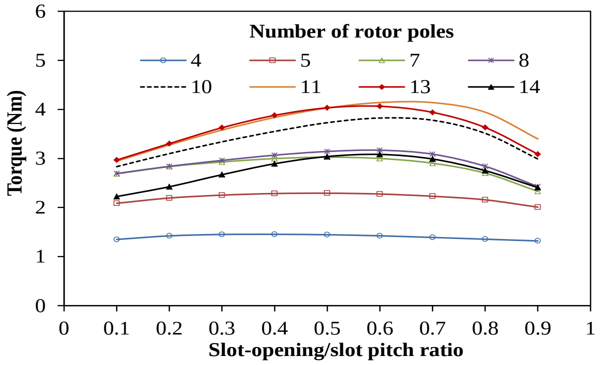


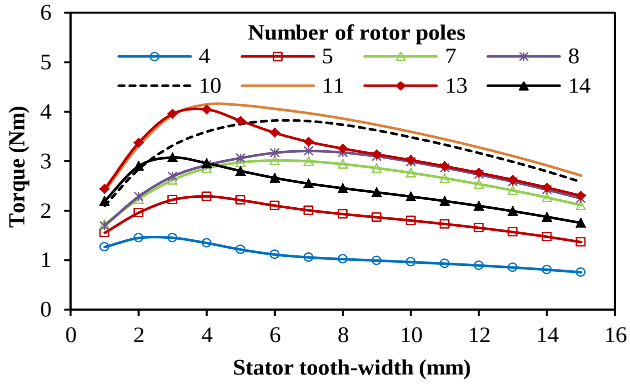
Figure 3: Variation of average torque with slot opening/slot pitch ratio.

3. IMPACT OF LEADING DESIGN PARAMETERS

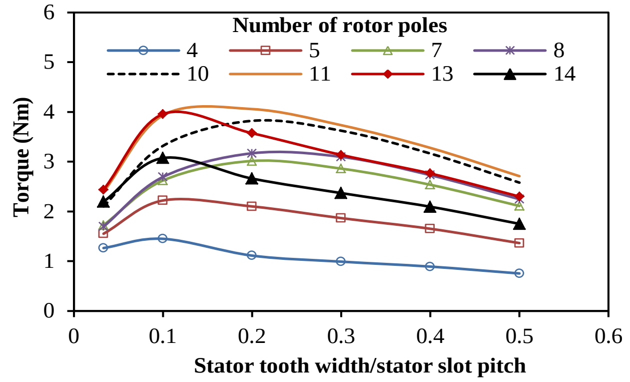
Since the overall electromagnetic performance of electric machines is influenced by their design parameters to a large extent, therefore, it is needful to investigate the effect of design parameters on average torque of the developed machines. The optimized machine parameters include: split ratio, rotor radial thickness and arcs, stator tooth-width and stator back-iron thickness. Figure 2 shows the variation of average torque with split ratio (which is defined as the ratio of the outer air-gap radius to the outer diameter of the machine). Larger torque is obtained in the 11-pole and 13-pole machines with optimum split-ratio value of about 0.7. It is worth mentioning that, the 4-pole machine suffers from poor torque density in all the analysed cases.

The variation of average torque with slot-opening/slot pitch ratio is shown in Figure 3. For each of the analysed rotor pole configuration, it is obvious that, there is an optimum value for maximum torque of the above mentioned design parameter as the radial length of slot-opening changes. The average torque increases initially with the slot opening/slot pitch ratio. As the tooth-tip width is small, there will be significant magnetic saturation of the tooth. Thus, as the tooth-tip width increases, the output torque will be increased. However, as the tooth-tip width continues to increase beyond a certain value, there may be decreased slot area for the winding and thus reduced phase current at the fixed copper loss condition, which will consequently lead to decreased output torque. Therefore, an optimum slot-opening/slot pitch ratio exists. Similarly, the variation of average torque with stator tooth-width in addition to its per slot pitch ratio is displayed in Figure 4.

Moreover, it can be seen from Figures 4 and 5 that, the average torque of the machines are very sensitive to both the back-iron thickness and the stator tooth-width as they affect the magnetic saturation as well as the available slot areas. Therefore, there is an optimum for either the back-iron thickness or the stator tooth-width. Further, the variation of average torque with both outer and inner arcs/pitch ratio is shown in Figure 6(a) and (b). Their respective optimum values are in the neighbourhood of 0.6-0.7.



(a) Torque versus stator tooth-width



(b) Torque versus stator tooth width/stator slot pitch

Figure 4: Variation of average torque with stator tooth-width, i_d=0.

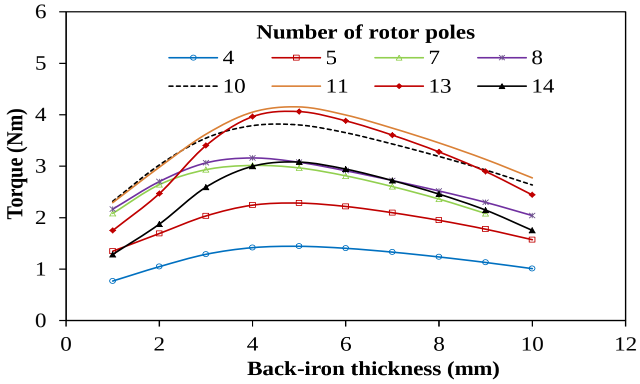
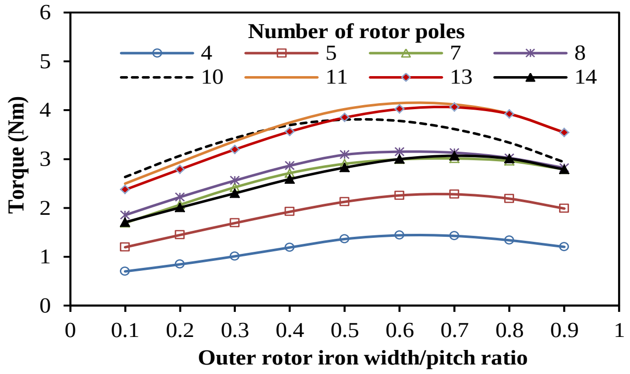
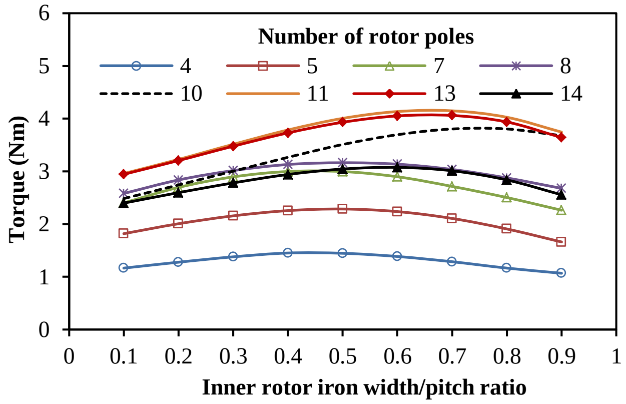


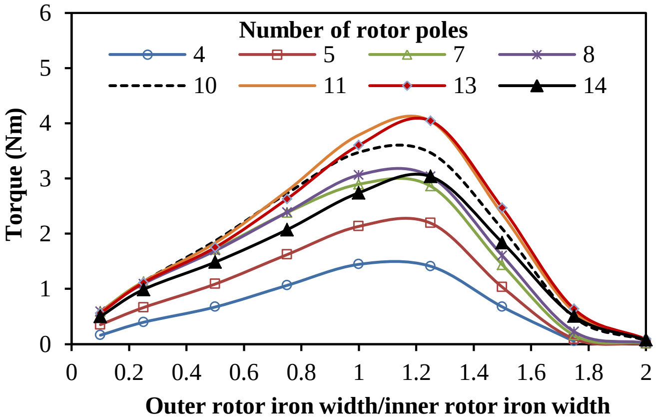
Figure 5: Variation of average torque with outer stator back-iron thickness, i_d =0.



(a) Torque versus outer rotor iron width/pitch ratio pole



(b) Torque versus inner rotor iron width/pitch ratio pole



(c) Outer rotor iron width/inner rotor iron width

Figure 6: Variation of average torque with outer and inner rotor pole arc.

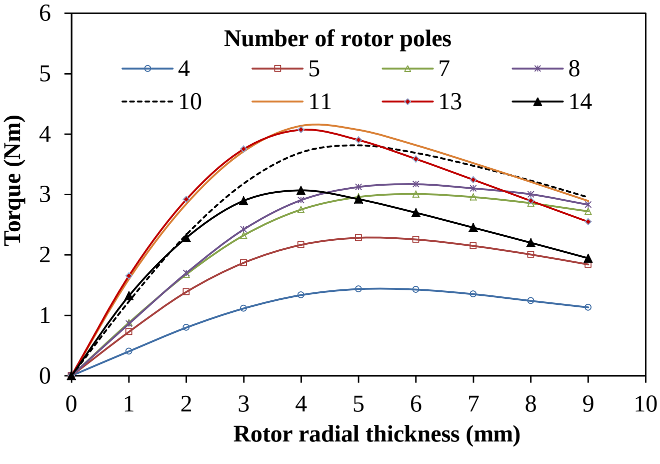


Figure 7: Variation of average torque with rotor radial thickness, i_d=0.

Similarly, the variation of average torque with the rotor radial thickness is depicted in Figure 7. An optimum rotor radial thickness will be obtained when there is a balance between the saturation effect due to thinner rotor radial width and the impact of small slot area due to the effect of over enlarged rotor radial thickness. A compromise between these two situations will yield an optimum result. The optimum value of the rotor radial thickness is approximately 4mm.

4. CONCLUSION

The impact of leading machine design parameters on the average torque is investigated. A comparative study of the influence of their varying rotor pole numbers is also given. The analysis reveal that, in order to obtain the maximum torque, the machine's optimal design values obtained due to saturation of the different electromagnetic reactions resulting from the changing values of the main design parameters should be used. Overall, the analyzed machine having eleven rotor pole topology seems to possess the best average torque performance in the entire study; this is followed by the thirteen rotor pole machine. It worth noting that, the analyzed 4-rotor pole machine suffers from poor torque density syndrome.

5. ACKNOWLEDGEMENT

The first author would like to thank The Commonwealth Scholarship Commission, UK for the sponsorship to run a PhD programme at the University of Sheffield, UK, during which period this research was carried out.

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