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# Impact of design parameters on the performance of dual stator flux-switching permanent magnet machine

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**Abstract**
The impact of design parameters on output torque of dual stator permanent magnet machine is presented in this study. The considered design parameters are: aspect ratio, stator yoke size ($Y_t$), stator tooth width ($W_o$), rotor centrifugal size ($R_r$), rotor inner pole length per pole pitch ($R_i$), rotor outer pole length per pole pitch ($R_o$), inner magnet size ($PM_i$) and outer magnet size ($PM_o$). The largest torque value of approximately 4.66 Nm is obtained using the implemented optimal design parameters, at constant copper loss condition. It is revealed that the resulting output torque of the investigated machine would be dependent upon the used design geometric values and invariably on the slot areas and supplied phase currents. The obtained results are predicted by means of two-dimension finite element analysis (2D-FEA). The finite element analysis (FEA) predicted optimal value of aspect ratio, stator yoke size ($Y_t$), stator tooth width ($W_o$), rotor centrifugal size ($R_r$), rotor inner pole length per pole pitch ($R_i$), rotor outer pole length per pole pitch ($R_o$), inner magnet size ($PM_i$) and outer magnet size ($PM_o$) is 0.7, 3 mm, 4 mm, 5 mm, 0.6, 0.35, 4 mm and 3 mm, respectively.

**Keywords:** Aspect ratio, design parameters, dual stator and permanent magnet machine.

## 1. Introduction

Owing to the exciting output torque of dual stator permanent magnet machines compared to its one-stator counterparts, numerous researches on the performance of dual stator electric machines are currently being developed and investigated. Consequent upon this, a dual stator permanent machine with focus on the impact of its design parameters on average torque is developed and analyzed in this current investigation. Zou *et al*., (2017a) showed that design parameters such as magnet width, tooth width, etc. could affect the output performance of a given permanent magnet (PM) machine. Moreover, the optimal width of these design geometric parameters may not necessarily be the largest size, since the resulting electromagnetic performance of a given electrical device would depend also on the cumulative interactions from the magnetic fields owing to all the excitation sources; and thus, the generated useful flux harmonics in the system at that particular time. An additional study about the ample significance of geometric design variables on the electromagnetic output of permanent magnet (PM) machines is detailed in Zou *et al*., (2017b). Similarly, it is proved in Huynh *et al*., (2018) that both the length and height of permanent magnets are critical in determining the characteristics and output performances of a given electrical machine; the aforementioned performances include torque, power factor and efficiency. Above all, relative locations of the mounted magnets as well as the number of magnet layers of an electrical machine should be taken seriously during the design and optimization stage, since these positions and layers would greatly influence the resultant product of the machine's energy conversion activities. Additionally, the power factor and torque ability of an electrical machine could be improved by appropriate modification of the geometric design variables through adequate optimization process, in order to minimize the inherent leakage flux in the system; albeit, with a slight reduction in the useable flux linkage amplitude, as presented in Ahmed and Hussain (2018).

Further, design parameters and PM plans is re-emphasized in Li *et al*., (2018) to be vital in determining the overall performance of a given electrical machine, in addition to the natural effects of slot and rotor pole number arrangements on the device. Moreover, studies in Xiao *et al*., (2021) used individual-parametric scanning optimization approach to calculate the influence of geometric parameters on both torque ripple and output electromagnetic torque of a given permanent magnet machine; nevertheless, more accurate optimal geometric values could be obtained from a similar machine, if a global optimization technique is applied as suggested in Zhu and Liu (2011).

Studies in Zhou and Hua (2019) revealed that the number of stator poles of a given double stator PM machine would considerably affect its output performance, due to its direct impact on the resulting airgap flux densities and consequently on the induced-electromotive force and torque. The outcome of the pole number influence would be better if the magnetic field couplings between the different stationary parts are of minimal value. Meanwhile, impact of stator poles would invariably determine the resultant amount of winding factor and other machine characteristics, as highlighted in Souissi *et al*., (2017). Hence, the best electromagnetic performance of an electrical machine would then depend upon the right choice of rotor and stator pole number arrangements. It is reconfirmed in Xu *et al*., (2021) that both the winding factors and stator tooth numbers of an electrical machine would affect its output characteristics, though with minimal effect on the machine’s aspect ratio. The aspect ratio of a given electrical machine is approximately equal to ratio of the machine’s stator inner diameter to its outer diameter, if the airgap size is very small.

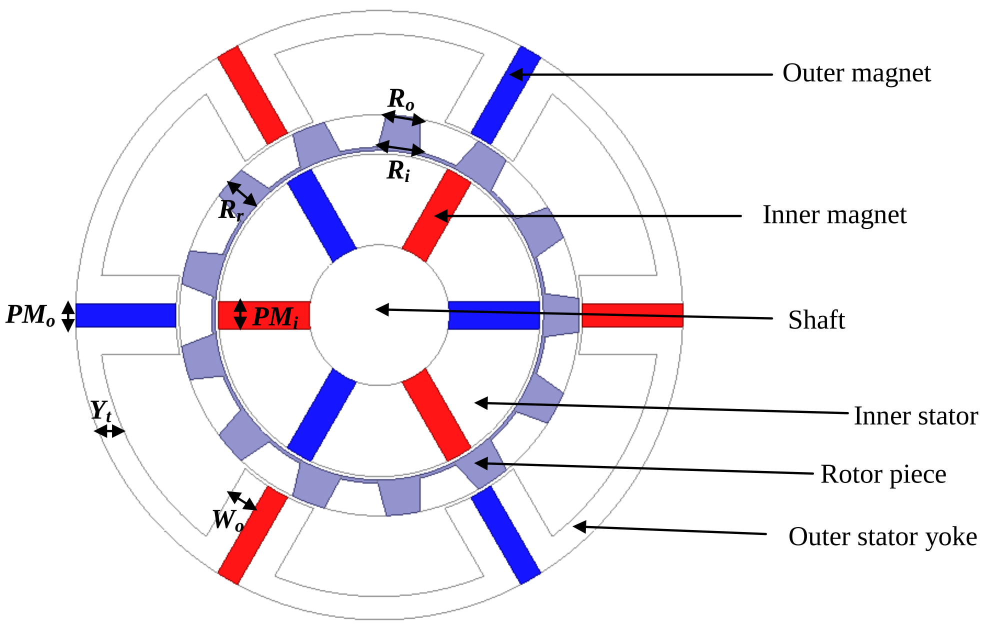



**Figure 1: Investigated dual stator machine outline**

Moreover, Wang *et al*., (2017) established that the aspect ratio of a given electrical machine would have substantial effect on other geometric parameters of the machine, such as the torque pulsations, average torque and power factor, etc. However, variations in aspect ratio of a machine would be compensated with a corresponding change in both the input current and winding spaces, and hence, the winding factor at constant copper loss condition. More importantly, the change in aspect ratio would simultaneously have inverse relationship between the machine’s power factor and output torque, where a direct relationship exists between the changing aspect ratio and power factor, while the varying aspect ratio has inverse relation with the corresponding machine’s output electromagnetic torque. The impact of design parameters on average torque is investigated and presented in this work; in order to guide and provide insight for electrical machine designers on the need to implement optimal design variables, so as to obtain the best output from the machine. The sections in this work are: introduction, materials and method, influence of design parameters and conclusion. The investigated machine model is displayed in Figure 1.

**2.0 Material and methods**

The implemented core and magnet materials in this analysis are steel and neodymium-iron-boron, respectively. The simulation is carried out with a 16G RAM Desktop computer using MAXWELL-2D, version 15.0 software. Note that two-dimensional finite element analysis (2D-FEA) is used in predicting the machine performance, in order to reduce the computational time associated with 3D-FEA computations, though the 3D-FEA usually has fairly higher precision compared to the 2D-FEA. The developed machine model has two stators: (1) Outer stator with salient poles having sandwiched magnets of opposite polarities. (2) Inner stator with different partitions having magnet in each segment, portrayed with red and blue colours.

It is worth mentioning the inner and outer magnets are arranged such that the inner and outer magnet would have opposite polarities; again, the adjacent magnet in each stator would also have opposite polarity with each other. More so, an inherent genetic algorithm procedure of the employed Maxwell software is used to estimate the machine geometric dimensions at constant copper loss condition. Nevertheless, parametric scanning of these geometric parameters is also undertaken in this study for ease of assessment of the maximum average torque, using each design parameter one at a time.

Moreover, the cup-shaped rotor of the investigated machine is situated in-between the inner and outer stators. As earlier mentioned, rotor is made of steel, though built in a ring form; the main job of the rotor is to modulate the magnetic fields from both the armature windings and permanent magnets, for ensuing torque production. The overall size of the developed model is 90 mm; it has an effective axial length of 25 mm. There is direct relationship between the conductor slot area and phase resistance ($R_\phi$) and hence, the root mean square (rms) phase current, at constant copper loss as given in equation (1). Similarly, the output torque (*T*) and power (*P*) of a dual stator flux-switching permanent magnet machine is expressed in the mathematical equations of (2) and (3), respectively.

$$R_\phi = \frac{2\rho\big(2(L+L_e)mN_\phi\big)}{Ak_f P_s} \tag{1}$$

where $L$ and $L_e$ are the machine's active stack length and end-winding length, respectively, $A$ is per slot area, $k_f$ is the winding factor, $m$ is number of phases, $P_s$ is the stator pole number, $\rho$ is the resistivity of the conductor material and $N_\phi$ is per phase number of turns (Evans and Zhu 2015).

$$T = \frac{\sqrt{2}\pi^2 kk_f k_{sr}\eta P_r B_{\max} JDL}{4P_s} \tag{2}$$

$$P = \frac{\sqrt{2}\pi^3 kk_f k_{sr}\eta f B_{\max} JDL}{2P_s} \tag{3}$$

where $k$ is the fraction of excitation flux to total flux, $k_f$ is the fraction of fundamental flux linkage to peak flux linkage, $k_{sr}$ is the fraction of stator tooth size to pole pitch size, $\eta$ is the efficiency, $P_r$ is the rotor pole number, $f$ is the electrical frequency, $B_{max}$ is the peak airgap flux density, $J$ is the electric loading, $D$ is the inner stator diameter, and $L$ is the machine's active stack length (Li *et al*., 2016).

**3.0 Results and Discussions**

The machine's aspect ratio is critical in determining the output torque of a given electric machine. Figure 2 shows the results of the investigated machine over different machine aspect ratios. The largest output torque is obtained at an aspect ratio of 0.7. It should be noted that the influence of the aspect ratio would be a direct consequence of the slot area availability and magnet size. Thus, if the available slot area is significantly small due to excessive increase of the aspect ratio beyond the value of 0.7; then, the machine would yield a correspondingly low output torque. Similarly, the variation of the stator yoke size, $Y_t$, is depicted in Figure 3.

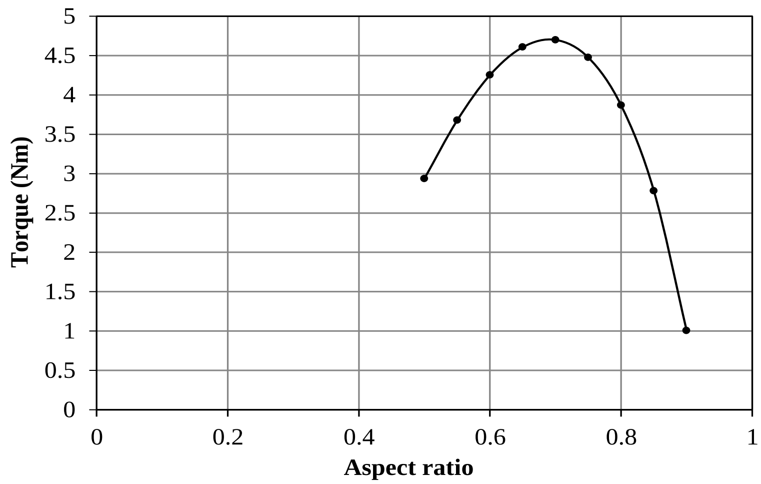



**Figure 2: Torque variation aspect ratio**

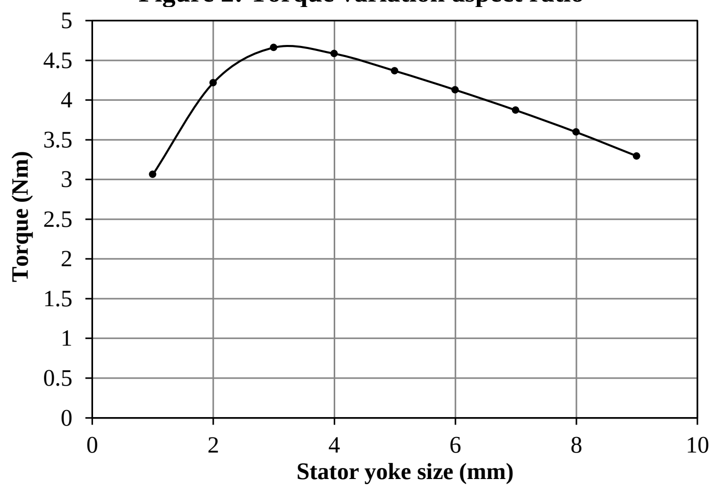



**Figure 3: Torque variation with stator yoke size**

The maximum value of torque is realized when the stator yoke size is about 3mm. Small size of the stator yoke may escalate/amplify the saturation level of the core, while a large stator yoke size beyond 3 mm would negatively affect the slot area and amount of the supplied current, at constant copper loss condition. These two extreme stator yoke size circumstances would decrease the resulting output torque; therefore, the optimal value of the stator yoke size is required to produce the best performance. Also, stator tooth size ($W_o$) variation with average torque is shown in Figure 4; the sensitivity of stator tooth size to the output torque is large. Again, the impact of this parameter, $W_o$, is dependent on the available slot area and the resultant supplied phase current. The best output torque of the machine is obtained when the stator tooth is approximately equal to 5 mm.

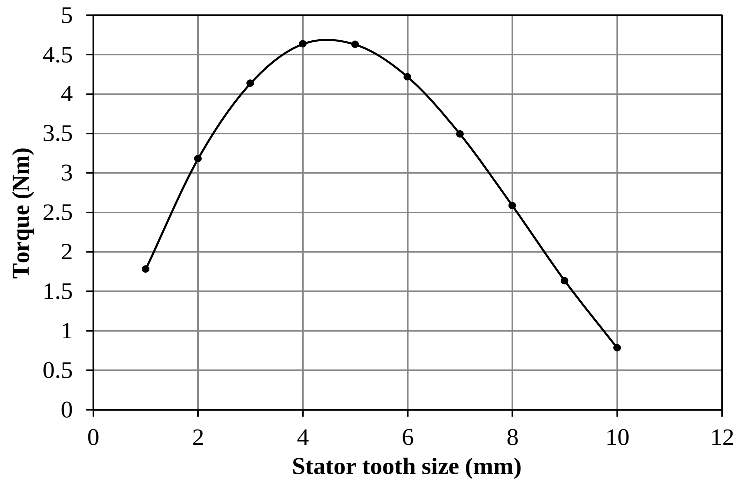



**Figure 4: Torque variation with stator tooth size**

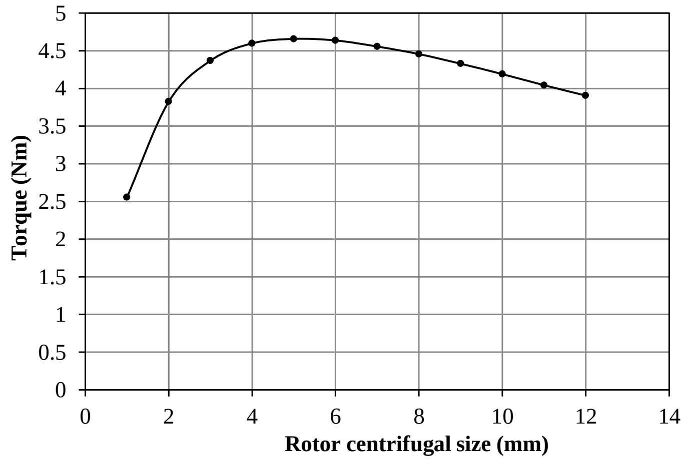
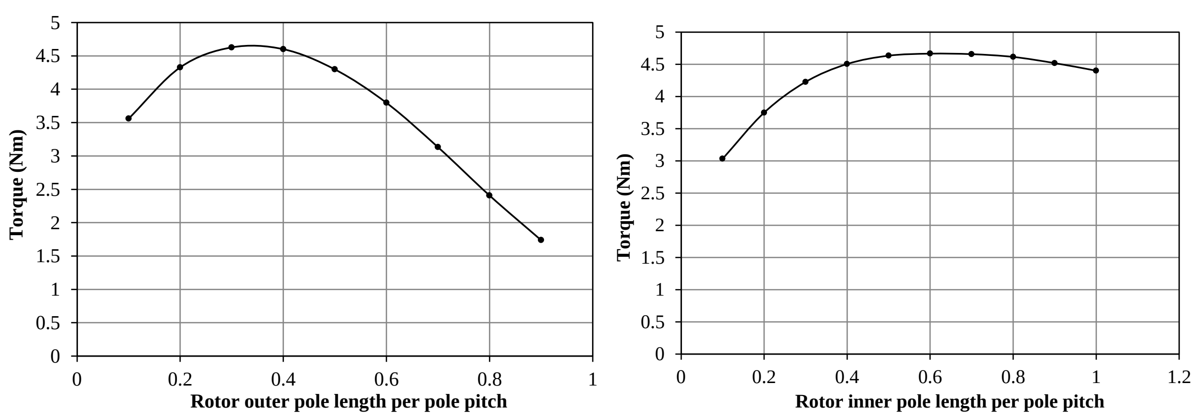



**Figure 5: Torque variation with rotor centrifugal size**

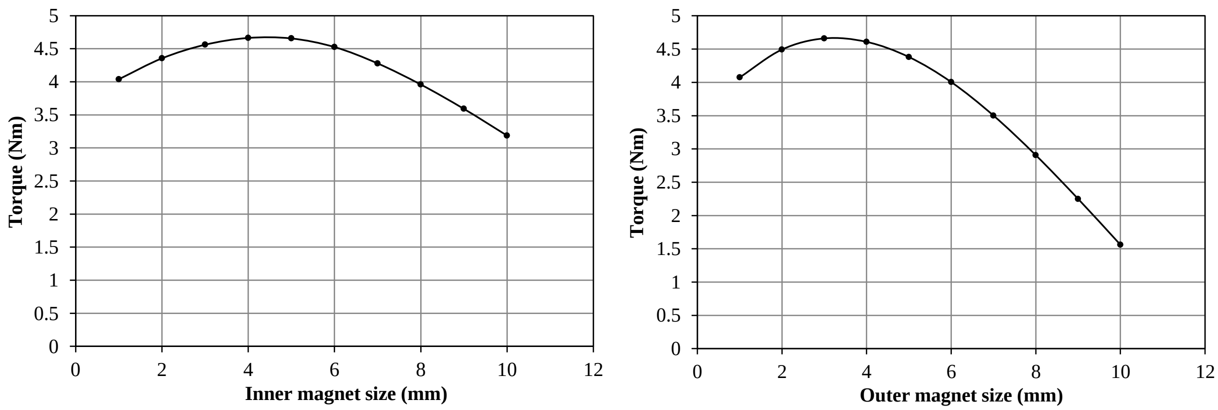
Figure 5 shows the variation of torque with rotor centrifugal size ($R_r$). Rotor centrifugal size of about 5 mm seems to be the best in order to generate the largest output torque. It is worth noting that very low value of the rotor centrifugal size would produce low output torque due to saturation effect of the armature reaction and a very large centrifugal size of the rotor would also produce low output torque due to its negative influence on the conductor slot areas; thus, a compromise would be necessary for an optimum performance.




(a) Torque versus rotor inner pole length per pole pitch (b) Torque versus rotor outer pole length per pole pitch

**Figure 6: Torque variation with rotor pole length per pole pitch**

Further, the variation of rotor inner and outer pole lengths per rotor pole ratio ($R_o$) and ($R_i$) are displayed in Figures 6 (a) and (b), respectively. The produced output torque in this case would be dependent on the amount of the flux linkage around the machine's airgap produced by the two varying geometric parameters at a given time. It is shown that in order to obtain the highest value of torque under this condition, then, inner and outer rotor pole length of about 0.6 and 0.35 per pole pitch are needed, respectively. Furthermore, the inner and outer permanent magnet sizes are varied in Figure 7. If 4 mm and 3 mm magnet sizes are adopted in the inner and outer stators of the investigated machine, then, the most promising machine performance would occur. It should be noted that extreme values of these geometric parameters may not yield the most favourable torque, owing to its direct dependence on both conductor area sizes and applied phase currents.




(a) Torque versus inner magnet size (b) Torque versus outer magnet size

**Figure 7: Torque variation with magnet size**

## 4.0. Conclusion

The impact of design parameters on the output torque of dual stator flux-switching permanent magnet machine was presented. The investigation showed that resultant torque of the machine was a function of its geometric design parameters, and hence, the availability of conductor slots spaces and consequently the supplied phase current. Sensitivity response of the aspect ratio and stator tooth size to average torque was considerably higher than the ones of the other compared design elements. An average torque of approximately 4.66 Nm was realized from the machine at fixed copper loss condition. The developed machine would be suitable for direct drive applications, especially at low operating speed.

## References

Ahmed, A., Husain, I., 2018. Power factor improvement of a transverse flux machine with high torque density. IEEE Transactions on Industry Applications, 54, 4297–4305.

Evans, D.J., Zhu, Z.Q., 2015. Novel partitioned stator switched flux permanent magnet machines. IEEE Transactions on Magnetics, 51(1): 1–14.

Huynh, T.A., Hsieh, M.F., Shih, K.J., Kuo, H.F., 2018. An investigation into the effect of PM arrangements on PMa-SynRM performance. IEEE Transactions on Industry Applications, 54, 5856–5868.

Li, D., Gao, Y., Qu, R., Li, J., Huo, Y., Ding, H., 2018. Design and analysis of a flux reversal machine with evenly distributed permanent magnets. IEEE Transactions on Industry Applications, 54, 172–183.

Li, Y., Bobba, D., Sarlioglu, B., 2016. A novel 6/4 flux-switching permanent magnet machine designed for high-speed operations. IEEE Transactions on Magnetics, 52, 1–9.

Souissi, A., Abdennadher, I., Masmoudi, A., Marignetti, F., Stefano, R.D., 2017. Feature investigation of a T-LPMSM following the selection of its slot-pole combination. IEEE Transactions on Industry Applications, 53, 1009–1017.

Wang, Y., Bacco, G., Bianchi, N., 2017. Geometry analysis and optimization of PM-assisted reluctance motors. IEEE Transactions on Industry Applications, 53, 4338–4347.

Xiao, Y., Zhu, Z.Q., Jewell, G.W., Chen, J., Wu, D., Gong, L., 2021. A novel asymmetric rotor interior permanent magnet machine with hybrid-layer permanent magnets. IEEE Transactions on Industry Applications, 57, 5993–6006.

Xu, F., He, T., Zhu, Z.Q., Wang, Y., Cai, S., Bin, H., Wu, D., Gong, L., Chen, J., 2021. Influence of slot number on electromagnetic performance of 2-pole high-speed permanent magnet motors with toroidal windings. IEEE Transactions on Industry Applications, 57, 6023–6033.

Zou, T., Li, D., Qu, R., Jiang, D., Jian Li., J., 2017a. Advanced high torque density PM vernier machine with multiple working harmonics. IEEE Transactions on Industry Applications, 53, 5295–5304.

Zou, T., Li, D., Qu, R., Li, J., Jiang, D., 2017b. Analysis of a dual-rotor, toroidal-winding, axial-flux Vernier permanent magnet machine. IEEE Transactions on Industry Applications, 53, 1920–1930.

Zhou, L., Hua, W., 2019. Influences of stator teeth number on PM coupling levels of co-axial dual-mechanical-port flux-switching PM machines. IEEE Transactions on Magnetics, 55, 1–7.

Zhu, Z.Q., Liu, X., 2011. Individual and global optimization of switched flux permanent magnet motors. In: Proceedings of IEEE International Conference on Electrical Machines and Systems, Beijing, China, pp. 1–6.