



THE IMPACT OF STATOR TOOTH AND POLE COMBINATIONS ON OUTPUT OF A DUAL STATOR ELECTRIC MACHINE

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ABSTRACT

Due to the great influence of stator tooth and rotor pole combinations of electric machine on its output performance; the feasible permutations of these machine variables and its resulting electromagnetic effects on the output characteristics of a dual stator (DS) electric machine were analyzed and quantitatively compared in this study, for overall optimal yield. Finite element analysis technique was employed in the predictions through MAXWELL-2D computational software. The considered stator number (N_s) was six (6) while its corresponding rotor pole numbers (N_r) were: 10, 11, 13 and 14 i.e. for N_s/N_r being 6/10, 6/11, 6/13 and 6/14, respectively. The study shows that machine type having 6/11 i.e. 6-stator tooth with 11-pole number would exhibit the largest flux linkage amplitude, reasonably high voltage at low operating current and most promising torque in relation to the deployed magnet volume, albeit; with low operating speed range. The 6/10 and 6/14 machine topologies would have considerably high amount of torque ripple coupled with very low output performance in comparison to its equivalent 6/11 and 6/13 machine types. Regrettably, high value of magnetic force on the rotor is acquired from 6/11 machine type. Consequently, the 6/11 machine type would most likely suffer from greater mechanical instability amongst other compared machine types; notwithstanding its other competitive merits.

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1.0 Introduction

Discussions on dual or double stator machines have drawn global attention of researchers over the decades, owing to its numerous merits over its single stator counterparts; ranging from enhanced thermal management, improved efficiency, larger torque and power densities, to higher fault-tolerant and reliability, amongst other advantages (Ali *et al.*, 2021). Both the open-circuit torque and electromagnetic torque of a machine would be greatly affected by its applied number of poles, as demonstrated by Awah *et al.* (2022). Besides, right selection of pole and slot combinations could reduce or eliminate torque pulsation and other unwanted machine features (Choo *et al.*, 2022). However, this present research is centred on the resulting impact of stator tooth and pole arrangements of a dual stator (DS) permanent magnet (PM) machine on a number of performance indices.

Dual stator machines usually have higher mechanical complexity and cost than equivalent single stator machines; but this higher cost could be drastically reduced through application of consequent-pole design strategy, as demonstrated by Baloch *et al.* (2018). Zhao *et al.* (2020) established that similar analyses on dual rotor single stator configuration are also possible with almost similar trend in its resulting waveforms; however, with some noticeable differences on its output magnitudes.

In order to enhance the torque densities of existing dual stator machines, Gao *et al.* (2019) and Song *et al.* (2019) developed two kinds of dual stator machines while also considering the tooth and pole possibilities of

the machines. The developed machines by Gao *et al.* (2019) and Song *et al.* (2019) are all dual stator machines and are distinctively different from that of the developed machine in this present investigation, structurally and otherwise.

Pole arrangements of a machine would affect the machine's pole ratios Li *et al.* (2015), winding factors (Awah and Okoro, 2018b) and subsequently, its resulting electromagnetic performances. The reliance of electrical machine's output on its pole, winding factors and gear ratios is further ascertained by Hyoseok *et al.* (2017), Xie *et al.* (2019) and Cooke and Atallah (2017), respectively.

It is worth mentioning that the studied machine in this present investigation belongs to the flux-switching permanent magnet (FSPM) machine family. FSPM machines have its feasible stator tooth and pole number combination peculiarities. This feasibility and peculiarities would naturally depend upon the basic operations of such machine i.e. as generator (Shao *et al.*, 2020) and or as motor (Shi *et al.*, 2016). Determination of tooth and pole possibilities via magnetic gearing principles can be extended to other electric machines, as detailed by Huang *et al.* (2019). Nevertheless, the research by Jia *et al.* (2016) shows that that a machine with high pole number may be associated with huge number of losses and by extension low efficiency regardless of its tremendous electromagnetic yield.

Torque-speed path of a machine could be achieved by weakening its flux, usually by application of negative direct-axis (*d*-axis) current, which will customarily affect the resulting axis inductance. The flux-weakening strategy was applied in this present study; however, an extended torque-speed trajectory of a flux-switching machine could be obtained by appropriate modification of the machine's *d*-axis inductance, through mechanical flux-adjusters, as presented in Zhao and Liu (2023) with validated experimental proof. This wider speed coverage is a desired quality for electric vehicle and traction applications. Similarly, a wider speed range could also be obtained in a machine by adopting a spoke-type magnetic rotor, owing to the associated high flux-focusing potential of this arrangement, for enhanced power, torque and efficiency values, amongst other admirable performance qualities. Again, the *d*-axis inductance worth of the system would be improved through this spoke-type arrangement; though, with suitable optimization of the machine's other leading geometric variables, as established by Hu and Wang (2023). More so, power density and efficiency of a machine could be improved by employing suitable core materials, as presented in Hebri *et al.* (2023).

Overall, stator tooth and pole arrangements of a dual stator machine is was analyzed in this current study and its impacts on the machine's output are were also quantified, with a view to providing adequate guide to machine designers and practitioners on the need to implement suitable stator tooth and pole combinations, considering its consequent effects, for better-quality machine output.

2. Materials and Methods

Investigated machine diagram is displayed in Figure 1. It is a double stator machine with magnets mounted on both stators. However, the alternating current armature conductors are placed only on the outer stator slot areas. The stators are separated by a rotor having field-modulating pole pieces. Both Maxwell-2D and MATLAB softwares were applied in the analyses. It is possible to carry out similar analyses using analytical methods, but finite element analysis approach is chosen and implemented in this study, owing to its high prediction accuracy compared to analytical procedures, which are associated with some electromagnetic assumptions. More so, field-weakening technique is adopted in obtaining the torque-speed trajectory through application of the machine's direct-axis currents and adequate transformation of its axis variables. The considered stator tooth number (*N_s*) is 6 while the rotor pole numbers are: 10, 11, 13 and 14, i.e. *N_s/N_r* is: 6/10, 6/11, 6/13 and 6/14, respectively. The adopted pole numbers are chosen on basis of the established feasible combination principles provided in Awah and Zhu (2016). The predicted torque (*T*) is expressed in Eq. (1). The calculated magnetic force on the rotor axes is mathematically expressed in Eqs. (2) and (3), as implemented in Awah *et al.* (2023b). It is important to note that magnetic flux density amplitude plays major role in the output delivery of a given electric machine (Awah, 2023a and Awah, 2023b).

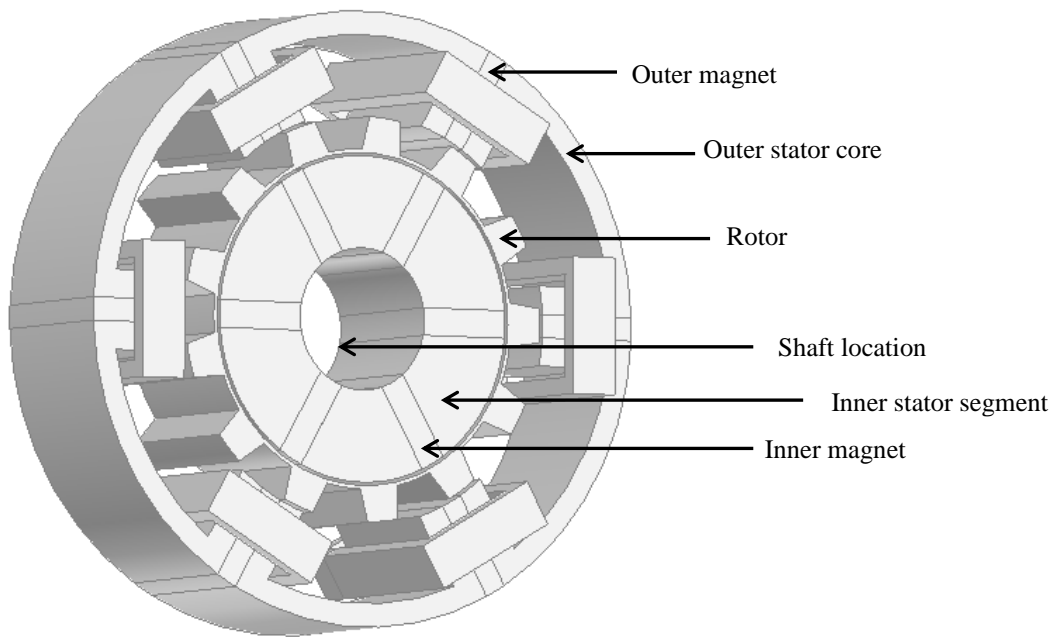


Figure 1: 3D diagram of the developed machine, 6/13(Awah, 2022)

$$T\omega = E_1I_1 + E_2I_2 + E_3I_3 \quad (1)$$

Where: ω is rotor speed, E_1 , E_2 and E_3 are three-phase voltages, I_1 , I_2 and I_3 are the matching phase currents (Oti and Awah, 2022).

$$F_x = \frac{1}{4} \int_0^{2\pi} \frac{B_r^2}{\mu_o} D l \cos \theta_s \Delta \theta_s \quad (2)$$

$$F_y = \frac{1}{4} \int_0^{2\pi} \frac{B_r^2}{\mu_o} D l \sin \theta_s \Delta \theta_s \quad (3)$$

Where: B_r is the radial flux density, D is stator inner diameter, l is stator axial length and θ_s is the stator angular coordinate.

It is worth noting that high amount of UMF would certainly influence the noise and vibration levels of a machine and may even reduce the life span of the machine (Awah *et al.*, 2018a).

3. Results and Discussion

Flux density contours of the machine configurations are presented in Figure 2; intensity of the flux is considerably high at the tips of both the stator and rotor teeth. The implemented flux density magnitude is 2.0 Tesla. Consequently, the resulting air-gap flux density wave forms of the machine types in one electric revolution are shown in Figure 3(a). The generated flux linkage outlines on no-load and at different speed settings are depicted in Figure 3(b).

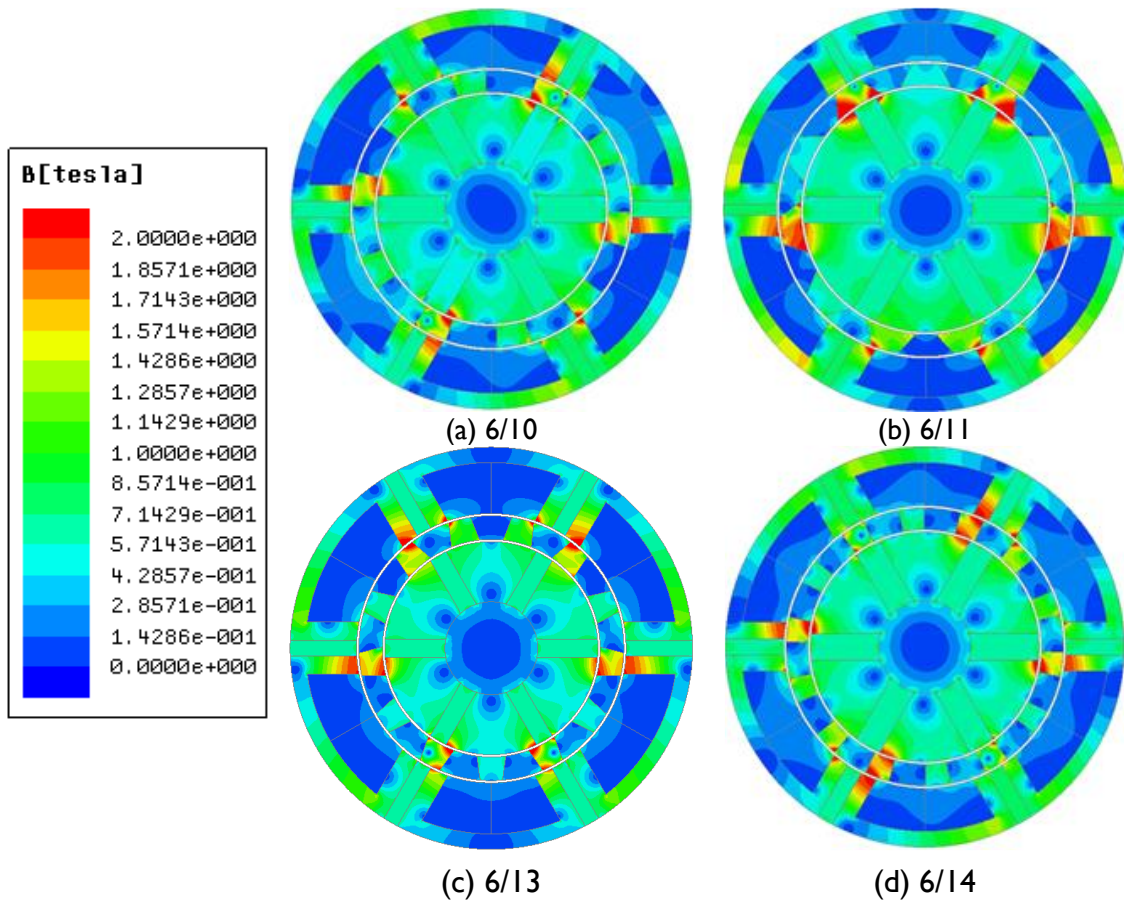
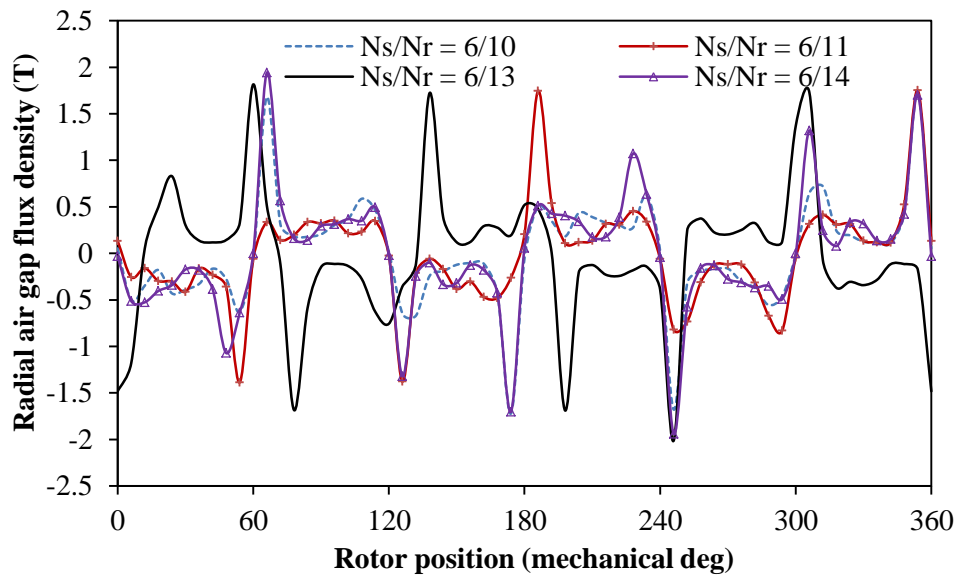
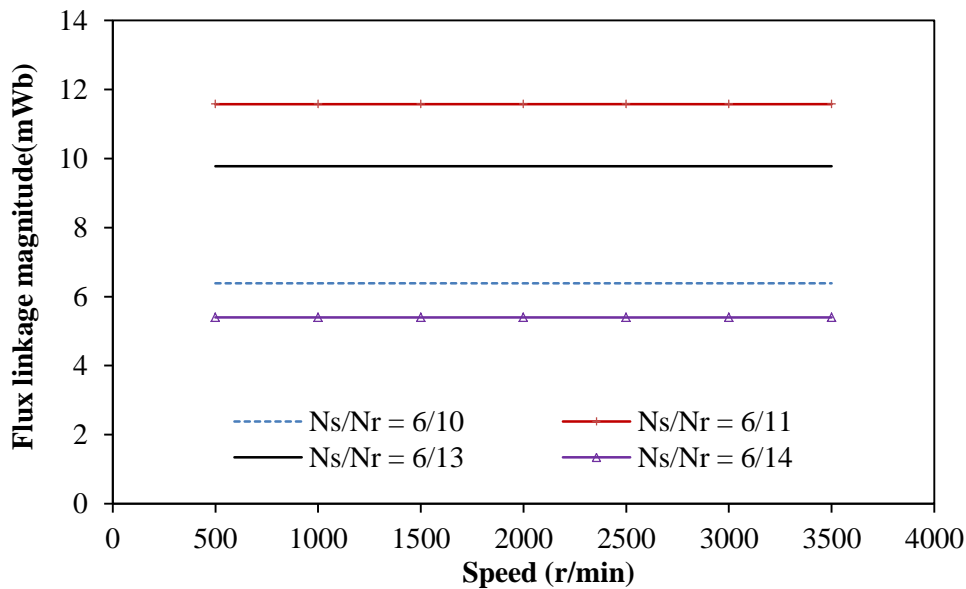


Figure 2: Magnetic flux density



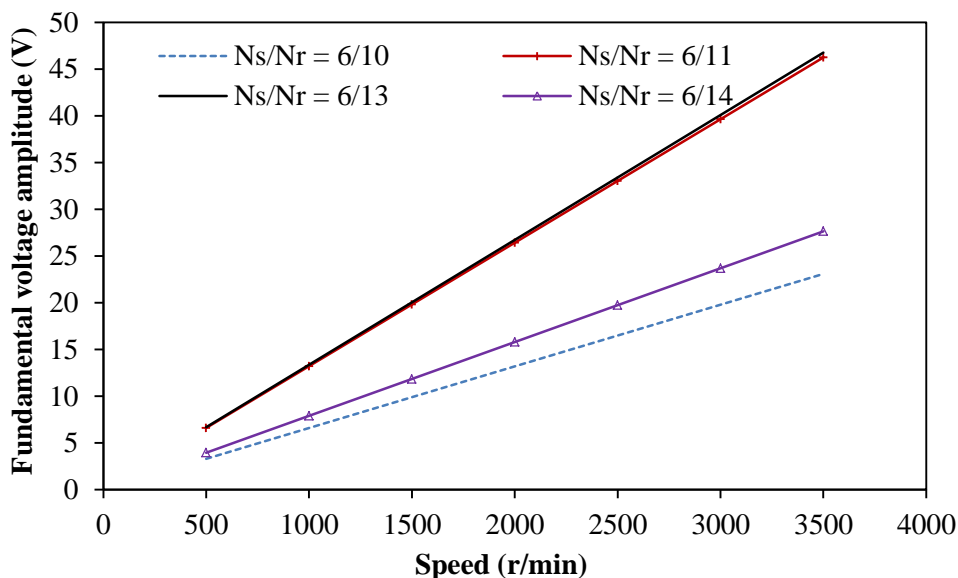
(a) Flux density versus rotor position



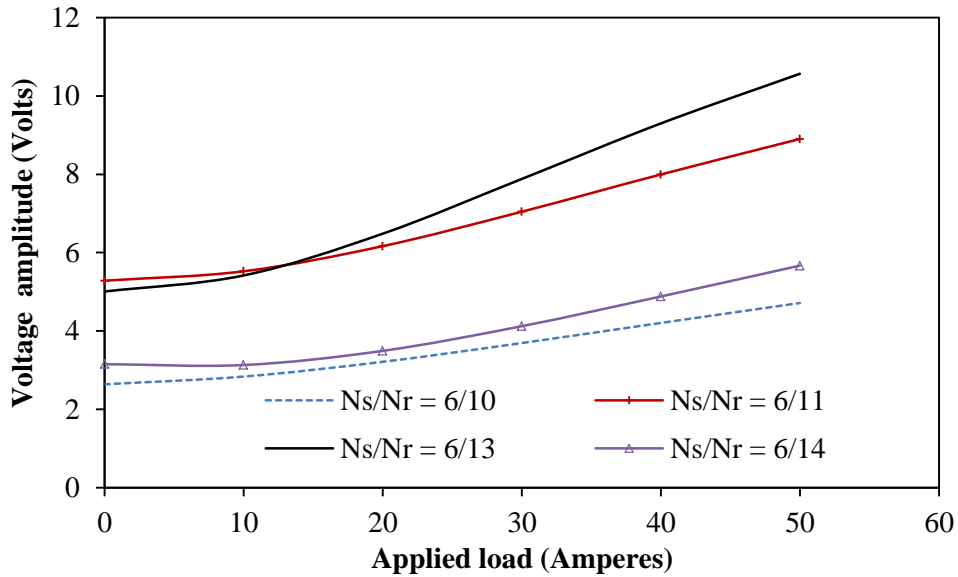
(b) Flux linkage versus speed

Figure 3: Flux density and linkage waveforms

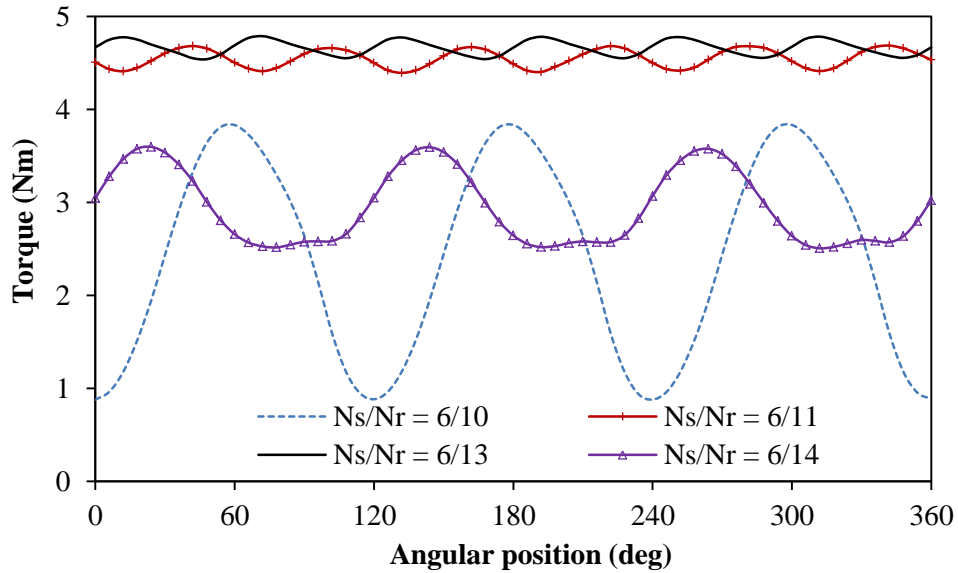
Figure 4 (a) shows the produced voltage values at varying speed. A linear relationship exists between the applied speed and generated voltage, in-line with theoretical impression. Voltage variations with applied current are compared in Figure 4 (b). It is observed that the 6/10 and 6/13 machine types would yield the lowest and highest voltage values, respectively; at extreme electric loadings. Meanwhile, the generated voltage values of 6/11 and 6/13 machine types are almost similar at all speed ratings, as presented in Figure 4(a), as well as at the rated current, as shown in Figure 4 (b). This similarity trend also repeated on the generated electromagnetic torque, as shown in Figure 5. It is worth mentioning that 6/10 and 6/14 machine types have dip pulsation effects on its torque, as shown in Figure 5 (a). It is worth noting that output torque of a machine is directly related to its induced-voltage. Thus, the presence of 3rd harmonic component of torque shown in Figure 5(b) is indications that the investigated machine would most probably possess even order voltage harmonics.



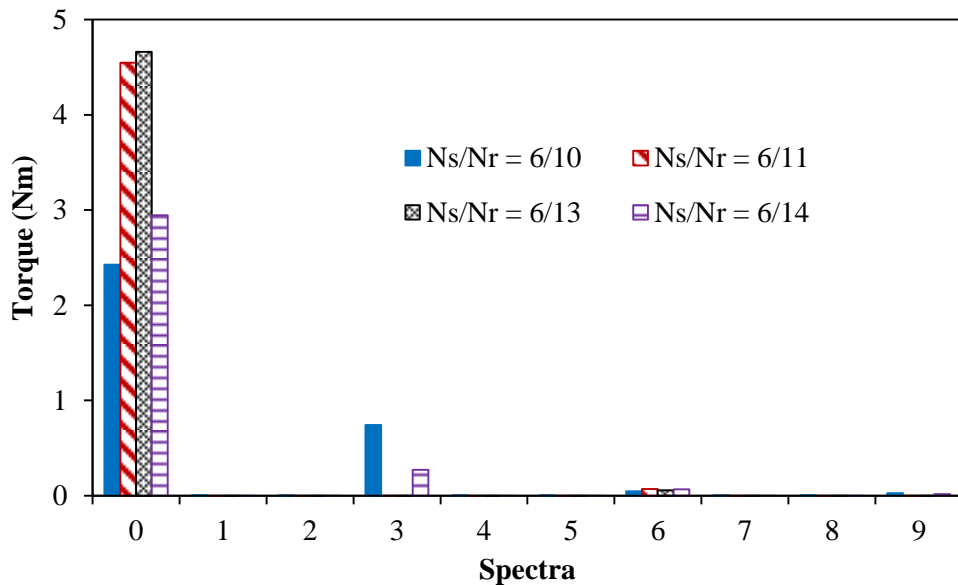
(a) Voltage versus speed



(b) Voltage versus load current
Figure 4: Comparison of voltage



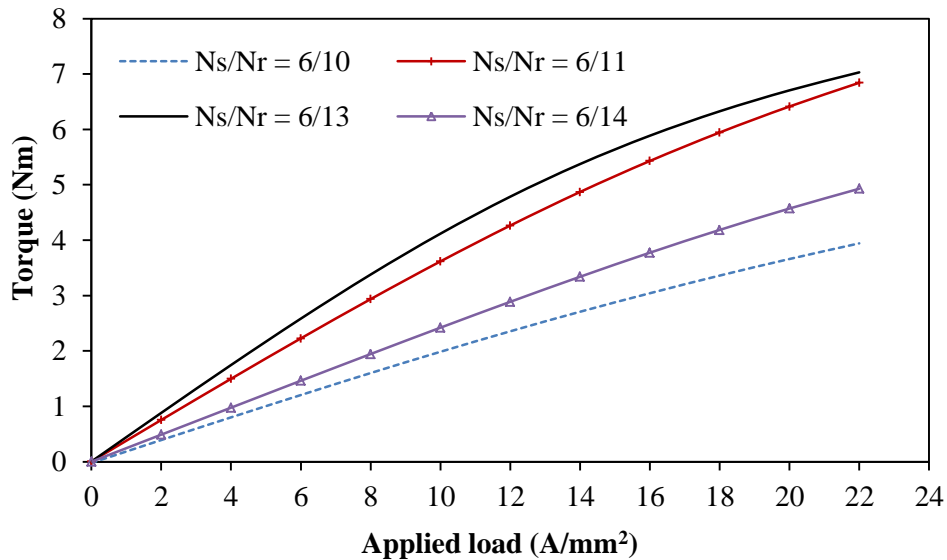
3. (a) Outlines



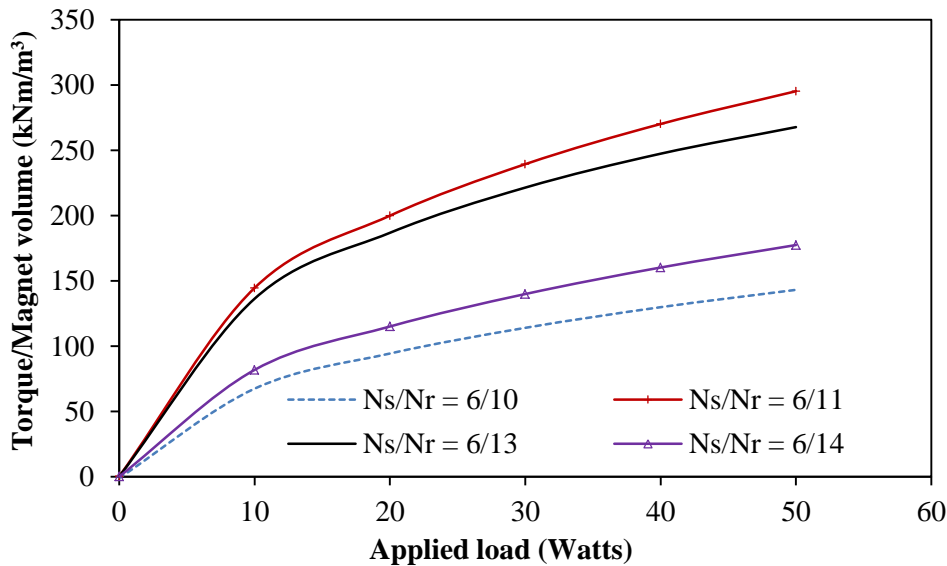
(b) Harmonics

Figure 5: Torque comparison at constant copper loss, 30W

The computed average torques at different current densities is compared in Figure 6 (a). The 6/13 machine produced the largest output torque at certain current density range, but 6/11 seems to possess highest ability to sustain electric overload at saturated condition. The 6/11 machine type is more promising in terms of its potential to generate the largest torque for a given volume of applied magnet material, as could be observed from Figure 6(b). Similarly, torque-speed routes of the analyzed machine types are presented in Figure 7. Although, 6/11 and 6/13 machine configurations have relatively high value of shaft torque compared to 6/10 and 6/14 equivalents, the latter has reasonably high speed coverage; which is an esteemed electric motor drive property. Nonetheless, the 6/10 and 6/14 machine categories may most likely face distortion issues during its drive period; particularly, at high speed, as could be observed from its reluctance torque outlines.

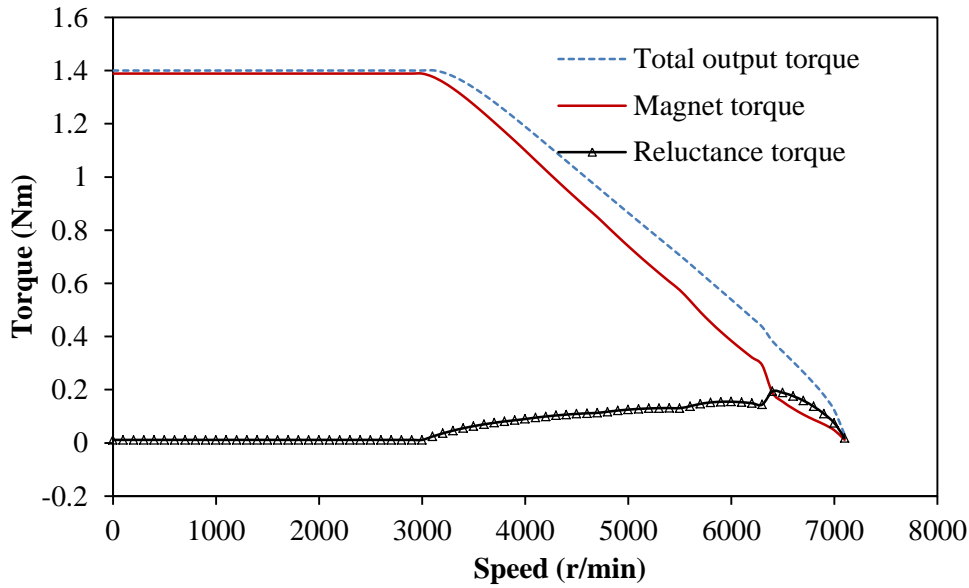


(a) Torque versus current density

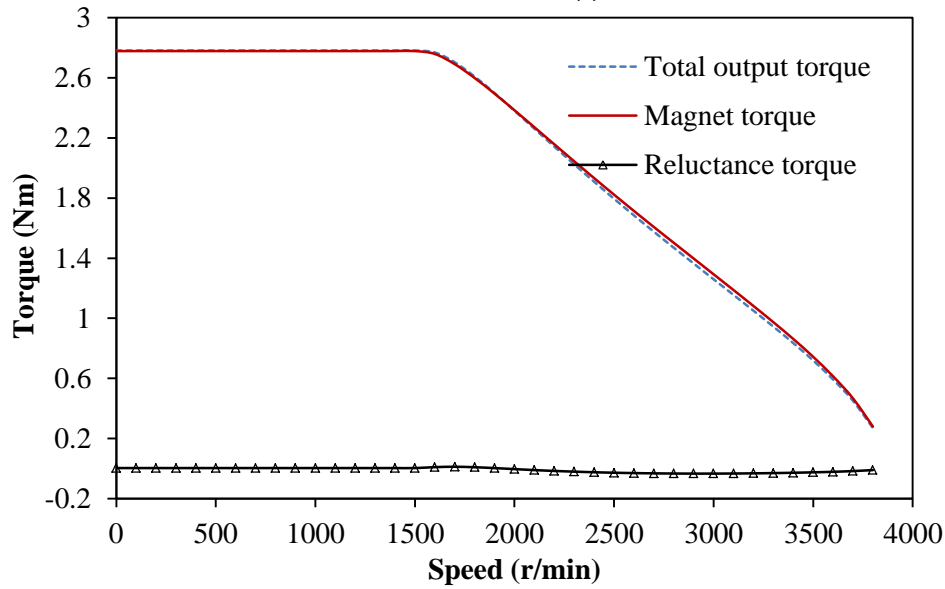


4. (b) Torque versus PM volume

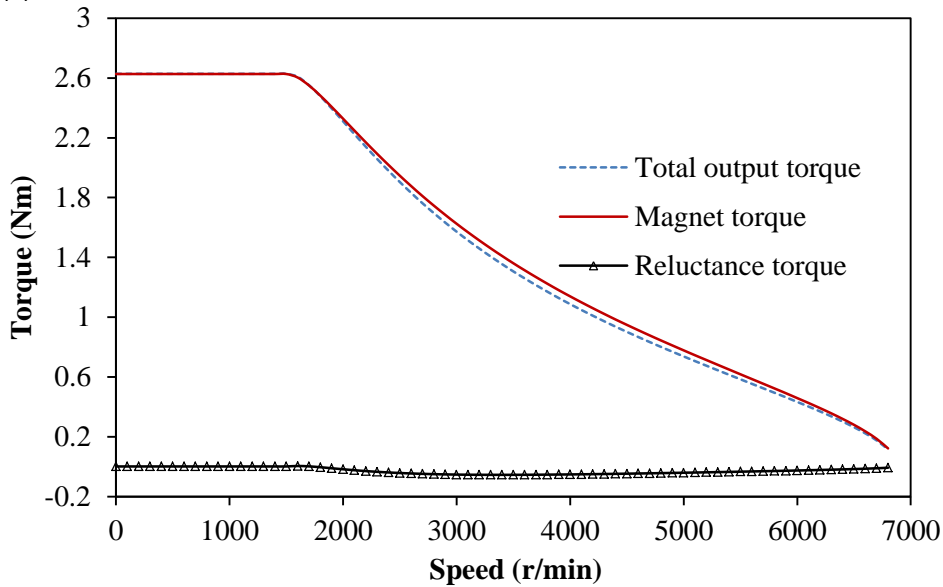
Figure 6: Torque comparisons at different load conditions



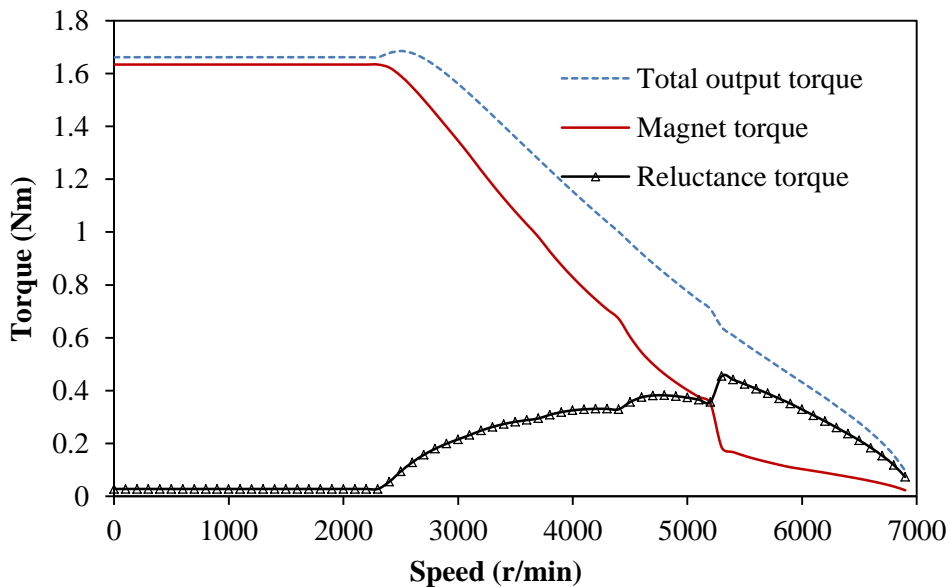
5. (a) 6/10



(b) 6/11



(c) 6/13



(d) 6/14
Figure 7: Torque characteristics

Resulting torque ripple values of the investigated machine types are displayed in Figure 8. Again, the calculated torque ripples are in agreement with the observations of Figure 5. The 6/10 machine topology has consistently exhibited the most deplorable electric machine characteristics.

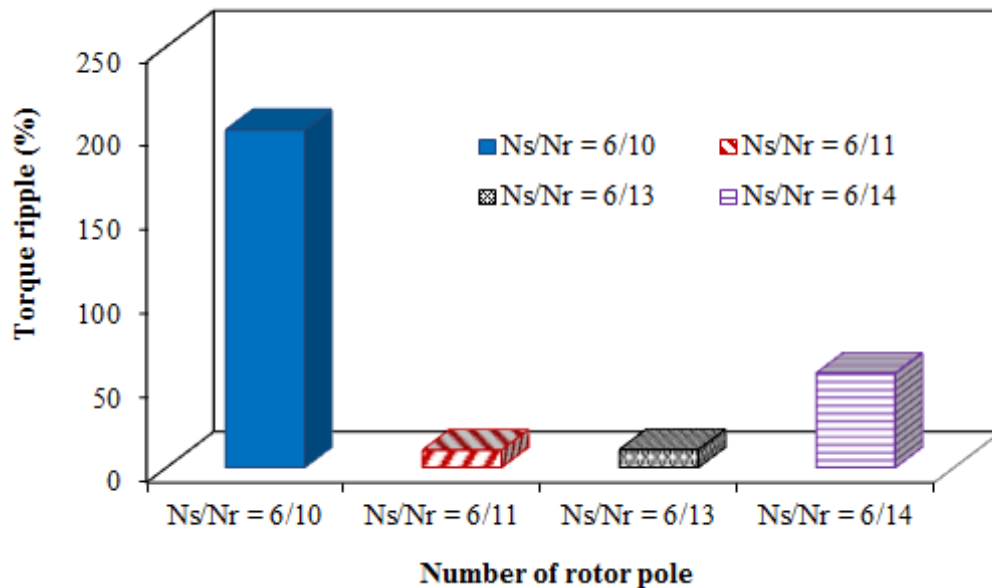


Figure 8: Torque ripple magnitudes at 15A

Magnetic force characteristics of the machine are presented in Figure 9. High value of unbalanced magnetic force (UMF) on the rotor is realized from the 6/11 machine type, this is followed by the 6/13 machine category. Negligible magnetic forces are obtained in the 6/10 and 6/14 machines types, owing to its suitable tooth and pole arrangements. This low value of magnetic force is a desired machine quality. Obviously, the resulting magnetic force would be large at low electric load condition, as shown in Fig. 9 (a) and (b).

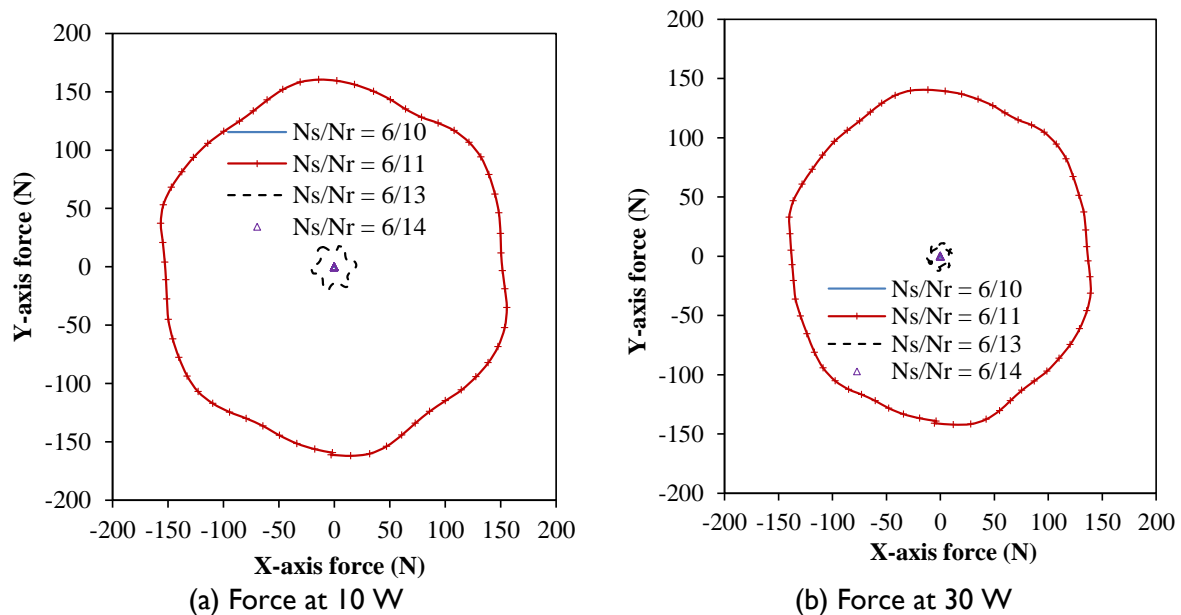


Figure 9: Rotor magnetic force

4. Conclusion

The impact of stator and rotor pole combinations of a dual stator permanent magnet machine is presented in this work. Most of the desirable machine outputs are produced by the machine type that is designated as 6/11; though, with a poorer speed coverage. It is observed that the machine types having 6/10 and 6/14 topologies exhibit poor output performances compared to its counterparts. Moreover, the machine type that is equipped with 13-pole would yield the most economic benefit, considering its higher torque in relation to the consumed lesser magnet material/volume. The analyzed machine would be most suitable in low speed and direct drive applications. The 6/11 machine type has the greatest potential against electromagnetic overloading; however, high amount of rotor magnetic force is also realized from the 6/11 machine type, and this is unattractive machine characteristics.

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