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Electromechanical analysis of a machine

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ABSTRACT

Output performances such as induced voltage and torque of an electric machine are investigated in this study, with particular reference to its pole number effects. Essentially, the implications of implementing the right numbers of pole and stator teeth or pole-slot combinations for optimal machine performance is presented in this study. The analyses are made using the 2D-finite element method. The study revealed that the investigated machine having 6 stator slots and 11 pole numbers i.e. 6S/11P has the highest amount of magnetic remanence, coercive force and flux linkage amongst the compared machine types. Consequently, these highest values would yield the largest output torque in the machine. Desirably, high output torque is also relatively realized in the 6S/13P machine type. Nevertheless, both the 6S/11P and 6S/13P machine types would be adversely affected by the large effect of magnetic force on its rotor. The greatest field-weakening ability, determined as a measure of the machine's speed ratio is provided by 6S/13P machine topology and this trait is desired in traction and propulsion systems. Predicted torque density of the machine types having 6S/10P, 6S/11P, 6S/13P and 6S/14P combinations at 30 W is: 246.55 kNm/m^3, 345.60 kNm/m^3, 372.70 kNm/m^3 and 210.42 kNm/m^3, respectively. By implication, the 6S/13P machine type is more competitive among the investigated machine types, considering its yield with respect to the employed magnet volume.

INTRODUCTION

Electrical machines' output performances are more or less dependent upon their poles. Thus, the basis of this present investigation is to understudy this pole relevance on a machine's output characteristics or generated features through a finite element approach. An electromechanical system has a tripartite arrangement or interrelationship amongst its electrical component, magnetic component and mechanical component; where, voltage, magnetic flux and speed are leading operating parameters, for the respective components.

Electromechanical machines or devices could be adopted in low-energy production like the transducers, or implemented in force production such as in actuators or solenoids; such a device could also be deployed in large-scale energy conversion processes and utilization, as found in generators and or motors (Fitzgerald, Kingsley and Umans, 2003). However, electromechanical interactions are capable of generating unwanted vibrations in the system, as presented by Holopainen *et al*. (2002). It is important to note that the class of electromechanical machine analyzed in this present study is an electric motor. A generalized circuit used in estimating the functionality of a typical electromechanical machine in all operating conditions is proposed by Kudarauskas (2006). However, the proposed generalized circuit utilized an analytical method in its prediction and analytical techniques which may likely have some level of inaccuracy, due to the associated assumptions of analytical studies; although this inaccuracy is usually trivial, it will contribute to the overall machine output.

Apart from the importance of poles in electrical machine analysis, it is established by Chen *et al*., (2011) that a flux-switching permanent magnet machine (FSPM) would produce larger output torque and other essential values when its stator tooth number is reduced by half; thereby, being both economical and compatible to commercialize. Note that the analyzed machine in this present study is an FSPM machine. Additionally, resulting outputs would also be influenced by the relevant geometric dimensions of the machine. This assertion about the advantageousness of reduced machine tooth number and its consequential larger torque density is reconfirmed by Chen *et al*. (2011), with validated experimental tests. Similarly, the influence of both low and high numbers of poles and structural effects are demonstrated by Liu and Zhu (2012) and Awah and Okoro (2017) to be a great influencer of machine output performances.

Improved machine output could be obtained from an FSPM machine by utilizing a flux-focusing technique during its design and operation, as highlighted in Shi *et al*. (2014). Note also that the flux-focusing technique is adopted in this present investigation, for torque enhancement. The deployment of the flux-focusing method in enhancing the output features of an electric machine is re-emphasized by Park *et al*. (2019). On the contrary, the flux-focusing technique advantage does not favour flux-modulated machines, as opined by Zou *et al*.(2017) owing to some form of flux obstructions and possible field leakages, arising from the machine's constructional organization. This flux impediment/weakness is intensified when the machine's pole ratio is high.

In a similar development, the studies presented by Zhang *et al*., (2017) revealed that FSPM machines that are configured with outer rotor topology will have their torque density decreased as the pole number increases. This is contrary to the results of an equivalent inner rotor configuration. It is important to note that the considered topology in this current study is an inner rotor with a dual stator configuration. Nevertheless, the findings in this current investigation are in agreement with the obtained results (Zhao *et al*., 2020).

Dual stator machines are usually wanted than their matching single stator machine types, for numerous electromagnetic output advantages (Song *et al*., 2019). Due to the numerous good qualities of dual stator machines over single stator ones, a lot of researchers have given great attention to its development and investigations, as demonstrated by Gao *et al*. (2017), Yu *et al*. (2019) and Awah (2022). However, dual stator machines normally have higher cost implications and most times with more complex mechanical structures than their equivalent single stator machines. Just like the presented predictions in (Martinez-Ocaña *et al*., 2019), the resulting output of a machine is influenced by its pole numbers, but its most competitive yields may not necessarily be attributed to the machine that has the highest number of poles; in line with the revelations in this current investigation.

In general, performance predictions of a dual stator (DS) permanent magnet (PM) machine of flux-switching origin are analyzed and compared amongst varying poles, for proper selection/identification of the most competitive machine configuration amid considered performance criteria.

MATERIALS AND METHOD

Materials

The considered machine diagram is displayed in Figure 1. The analyzed structure is realized through the use of a genetic algorithm optimization process and was developed by Awah (2022). Maxwell stress tensor analysis is utilized in predicting its magnetic forces while the transient solver mode is engaged in the other electromagnetic and electromechanical analyses. Electromagnetic torque (T_e) is given in Eq. (1), as implemented in Awah, (2020). The induced-voltage (E) expression is stated in Eq. (2). Moreover, it is inferred from Awah (2021) that the maximum value of induced-voltage is proportional to the machine's effective length and stator bore diameter. The outer stator size of the machine is 90 mm. The rated speed and current are 400 rpm and 15 A, respectively. Note that the calculations are conducted in one electrical cycle and on both load and no-load conditions. It has a double stator structure separated by a rotor and two (2) air gaps.

The applied stator and rotor core materials are steel while the magnets are made of rare-earth neodymium material. The conductors are made of copper.

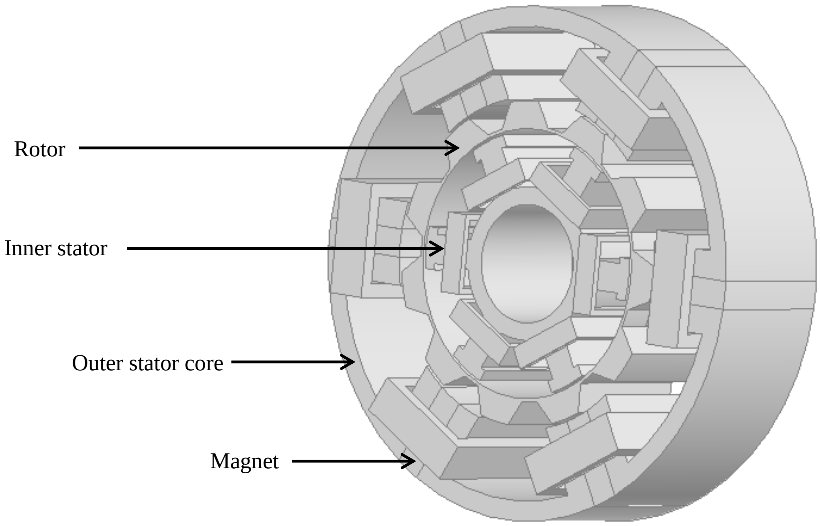


Figure 1: Analyzed machine assembly Awah, (2022).

$$T_e = 1.5P\left(\psi_m I_q + (L_d - L_q)I_d I_q\right) \qquad (1)$$

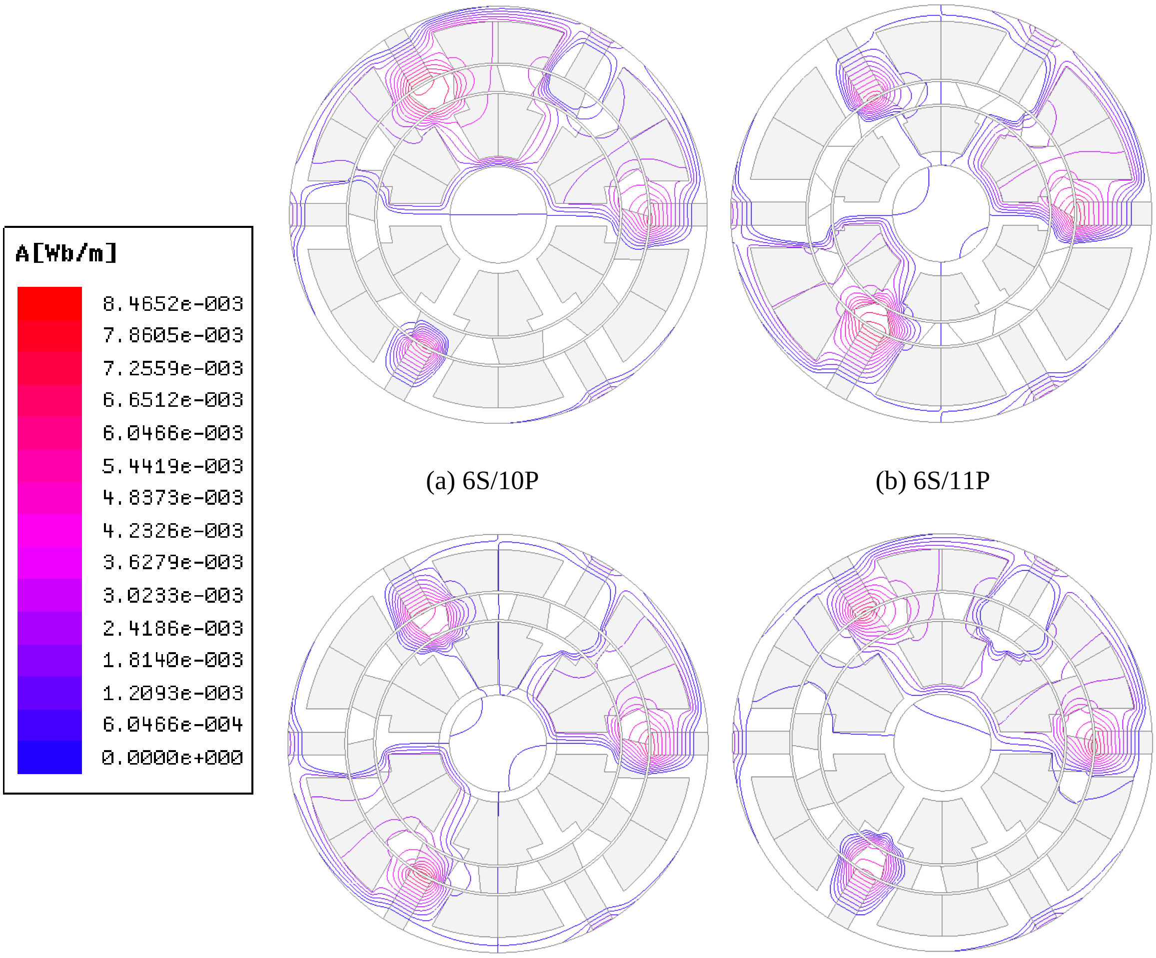
Where: P is the pole, ψ_m is the magnet flux linkage, I_d and I_q are the axis currents, L_d and L_q are the matching inductances (Chen *et al*., 2008).

$$E = -N\omega \frac{\Delta\varphi}{\Delta\theta} \qquad (2)$$

Where: N is the number of turns, ω is rotor speed, $\Delta\Theta$ is the change in rotor angle, $\Delta\varphi$ is the change in flux/pole (Awah and Okoro, 2021). However, the field-weakening potential of a PM machine is directly related to its axis inductance and the resulting magnet flux, as emphasized by Awah and Zhu (2016).

RESULTS AND DISCUSSION

The magnetic flux lines are presented in Figure 2. The flux line quantity per pole is inversely proportional to increasing pole number, as could be observed from the outer stator cores of the compared machine types in Figure 2. This inverse relation is because the resultant flux is estimated per pole; thus, a lesser quantity of flux would be distributed by higher pole number and vice-versa. The predicted magnetic remanence and coercive force or coercivity are presented in Figure 3 (a) and 3(b), respectively. 6S/11P machine configuration has a conspicuous amplitude of both magnetic remanence and its matching coercivity.



(a) 6S/10P (b) 6S/11P

(c) 6S/13P (d) 6S/14P

Figure 2: Magnetic flux lines

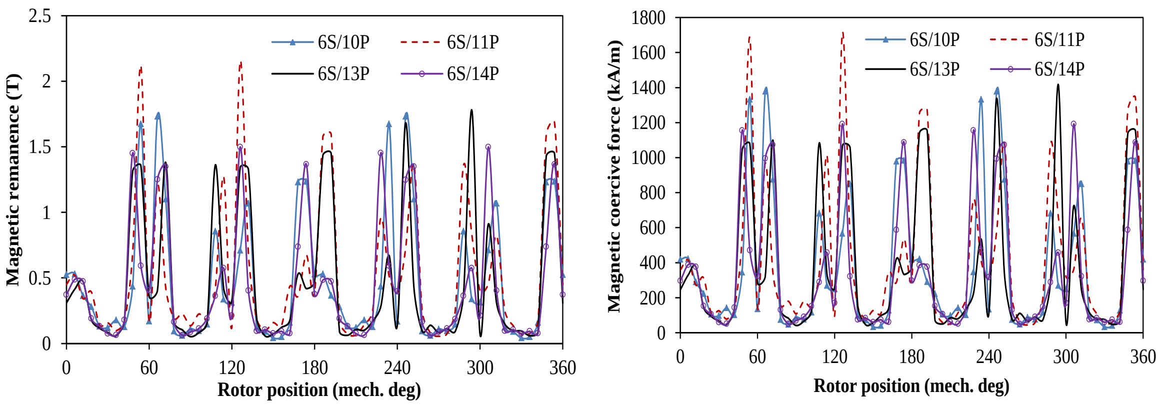


Figure 3: Magnetic remanence and coercive force (a) Remanence versus rotor position (b) Coercive force versus rotor position

Induced EMF or voltage outlines over different speed settings are shown in Figure 4. The most favourable outline is generated by 6S/11P machine type while the least performing model is 6S/10P. A similar trend is replicated in Figure 5; again, the lowest average torque is obtained from 6S/10P machine.

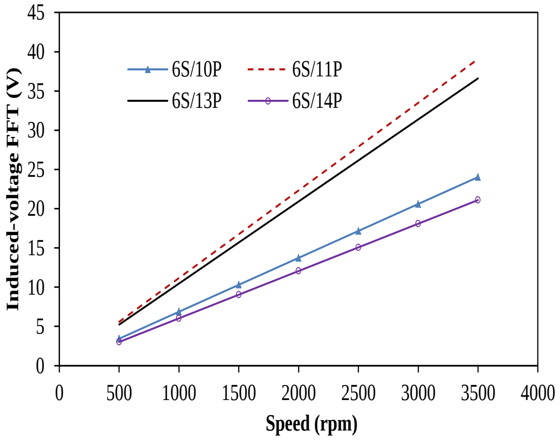


Figure 4: Induced-voltage outlines

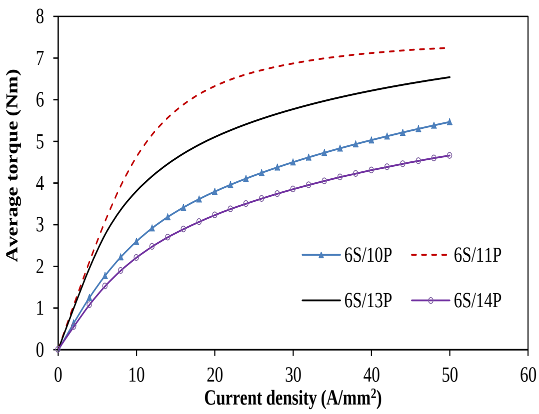


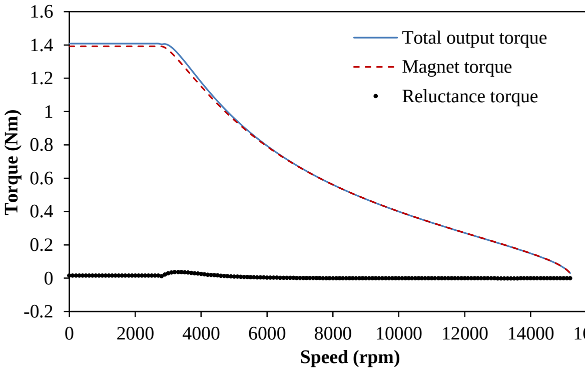
Figure 5: Torque versus current density

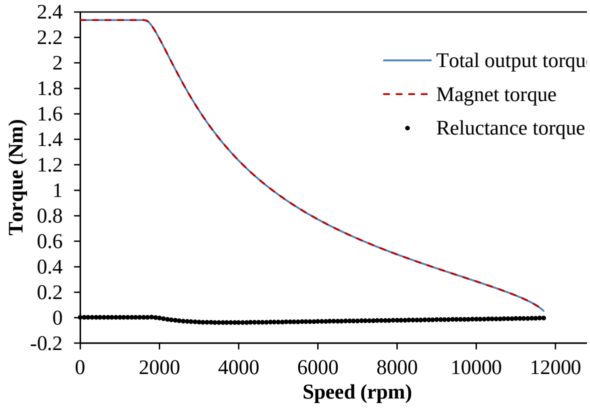
Torque-speed paths of the machine are depicted in Figure 6. It is revealed that the machine categories have varying base and maximum speeds, as shown in Figure 6(a)–(d). They also exhibit different field-weakening shapes. Estimated field-weakening values of the machine are provided in Table 1; these values are given as a ratio of maximum speed to the corresponding base speed. It is worth mentioning that 6S/13P has the most estimable field-weakening value, an admirable vehicle and drive quality. It is also noticeable that the entire machine types have almost zero reluctance torques.

Both 6S/13P and 6S/11P machine categories have relatively very high force magnitudes on the rotor compared to its equivalent 6S/10P and 6S/14P, which have nearly zero force values at a load of 30 W, as shown in Figure 7 (a). A lot of unpleasant machine characteristics could be encountered or developed in a machine by the virtue of its high magnetic force amplitude (Lan *et al.*, 2018). Predicted results of Figure 7(b) reveal that 6S/13P machine configuration has the highest torque value per applied magnet quantity, and this implies that 6S/13P machine type is cost-effective to deploy. The worst-case scenario of output torque per magnet quantity is realized from 6S/14P machine topology, in all simulation situations.

Table 1: Field-weakening Prediction

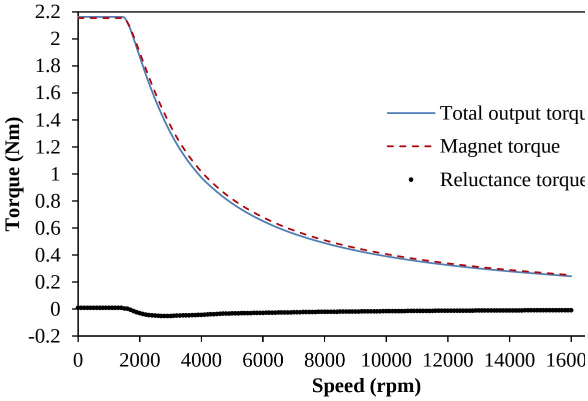
Item	**Value**			
Machine type	6S/10P	6S/11P	6S/13P	6S/14P
Maximum speed, rpm	15200	11700	16000	16000
Base speed, rpm	2800	1700	1500	2500
Maximum speed / Base speed	5.42	6.88	10.67	6.40
Axis inductance (L_d), mH	0.3169	0.5215	0.6105	0.3421
Current, A	15			
No-load magnet flux, mWebers	6.5589	9.6976	7.6894	4.1122

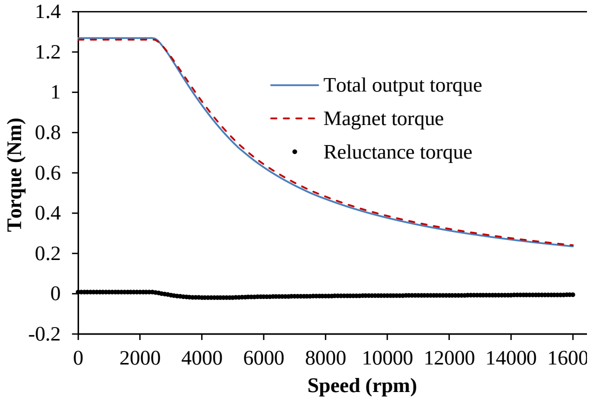




(a) 6S/10P

(b) 6S/11P

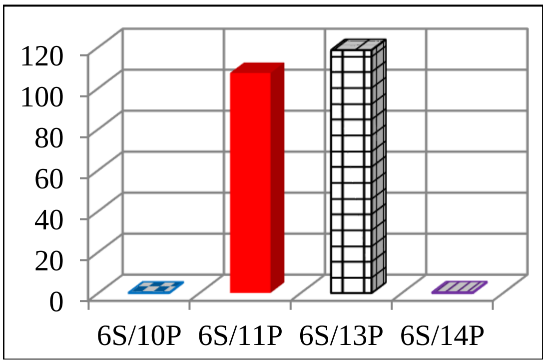


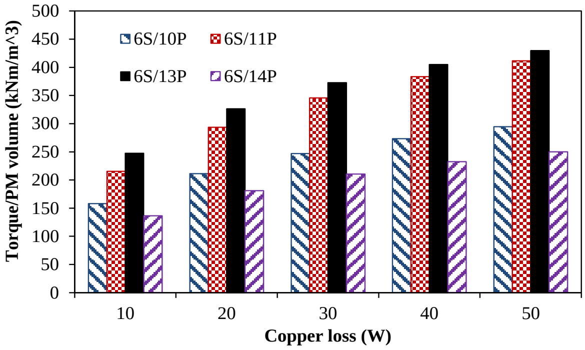


(c) 6S/13P

(d) 6S/14P

Figure 6: Comparison of torque-speed paths at rated load conditions.





(a) Force level at 30 W

(b) Torque per magnet volume versus copper loss

Figure 7: Force and average torque comparisons.

CONCLUSIONS

A double stator machine having four different poles is analyzed and presented. The investigated 6S/11P and 6S/13P have more admirable machine qualities than the other compared machine types; though, with a high amount of magnetic force, which is usually responsible for vibration and noise in the system and could be detrimental to the smooth operation of a machine. It is revealed that 6S/13P would exhibit the most desirable output torque considering the volume of employed magnet materials and consequently resulting lowest cost effect. 6S/13P model has the most favourable field-weakening potential. The machine types can be applied in both low-speed and high-speed traction and drive systems.

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