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Winding inductance predictions of a double stator machine

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ABSTRACT

The winding inductances of a double stator machine are analyzed in this study. Finite element analysis is deployed using MAXWELL-ANSYS software. It is revealed that the machines that have an even number of poles that is, 10-pole and 14-pole, exhibited a larger amount of both self and mutual inductance values. The 10-pole and 14-pole machine types have relatively larger direct-axis inductance compared to that of their 11-pole and 13-pole counterparts; nevertheless, with comparably lower quadrature-axis inductances. The machine types that have an odd number of poles seem to possess lesser sensitivity to their inductance-current relation, unlike its equivalent even number of pole categories. The predicted peak magnetic axis force value on the rotor of 10-pole, 11-pole, 13-pole and 14-pole machine varieties at 30 W is 0.18 N, 87.60 N, 10.95 N and 0.13 N, respectively. This implies that the 11-pole and 13-pole machine types would have a higher amount of noise and vibration and possible degradation than their equivalent 10-pole and 14-pole ones.

INTRODUCTION

Winding inductances of a machine play a major role in its resulting performance indices and characteristics. Therefore, finite element predictions of a machine's inductances, including the axes inductance as well as the mutual and self-inductances of the machine are studied in this research; to analyze its effect on the machine's output values, particularly, as it relates to its pole number modifications.

A conventional permanent magnet (PM) machine is designed such that the relative difference between its axes inductance is huge to account for adequate reluctance torque in the machine (Vukotić *et al.*, 2020). This dependency on axes inductance is termed as its saliency effect. On the contrary, the investigated dual stator machine in this current study naturally has almost zero value difference between its axes inductance and hence, with a consequential negligible reluctance torque worth. A machine's saliency profile is often influenced by its pole number (Thomas *et al.*, 2009) and also by its number of slots and winding pattern (Ni *et al.*, 2014); this may consequently result in mechanical instability in the system. Mechanical instability could also lead to a number of issues on the machine such as low reluctance torque, and increased electromechanical losses, among others (Yamazaki and Takeuchi, 2017).

It is worth noting that the resultant winding inductance values of an electrical machine are customarily affected by its supplied current magnitude. These current magnitudes particularly, in different phases and axes would certainly impact the resulting inductance characteristics of a machine; thereby, giving rise to cross-coupling non-linearity, as noted by Ibrahim *et al*. (2017) and (Mingardi *et al*., 2017). The knowledge and accurate prediction of winding axis inductances is critical in achieving optimal control of electrical machines, as provided in (Jang *et al*., 2011) and (Hu *et al*., 2018), amongst its other general impacts.

The fault-tolerance capability and thus, reliability of a machine is dependent upon its winding inductance (Zhao et al., 2021); nevertheless, these good qualities could be boosted by deploying multi-phase procedures and systems, as opined by Thomas *et al*. (2009) and Zhang *et al*. (2019).

Constructional or geometric model modifications and proper optimization application could be adopted to realize reasonable inductance values from an electrical device (Hu *et al*., 2021). Research has shown that winding inductances could be estimated faster using an analytical modelling approach compared to the use of finite element analysis (FEA) (Dutta *et al*., 2012, Lee *et al*., 2011); though, with slightly lesser accuracy. Note that FEA technique is implemented in this investigation.

In principle, the winding inductances and magnetic forces of a double stator electric machine are analyzed and compared in this research; for better insight into its output profile, especially, as it relates to pole number modifications. Basic information about the researched title is provided in section 1 (Introduction) while the applied method and materials are presented in section 2 (methodology). The results are discussed in Section 3 and conclusions are drawn in Section 4.

METHODOLOGY

The schematic and mesh contour of the analyzed model are depicted in Figure 1 (a) and (b), respectively. It is a double stator machine with a fit-in rotor. Alternating current (AC) armature windings are mounted in both inner and outer stator slots while the magnets are located only in the inner stator. The analyzed machine has six (6) slots and four (4) different poles, i.e. 10-, 11-, 13- and 14-pole. It is worth mentioning that small discrete mesh elements are applied in this study, for enhanced prediction; this is evident in Figure 1(b). The simulation was carried out on load conditions, using MAXWELL-ANSYS computational software. The utilized magnetic remanence is 1.2 Tesla. The machine is of 90 mm diameter having a 0.5 mm airgap size with an overall active length of 25 mm. Note that the cores are made with steel while the magnets are of rare-earth class. Maxwell stress tensor technique is affected in predicting the magnetic forces. The impact of winding inductances and magnetic force on the performance of a double stator machine is predicted and compared in this study amongst different numbers of poles. Predicted self-inductance (L_s) and mutual inductance (L_m) are computed using Eq. (1) and Eq. (2), respectively. Likewise, the direct-axis inductance (L_d) and quadrature-axis inductance (L_q) of the machine are predicted using Eq. (3) and Eq. (4), respectively.

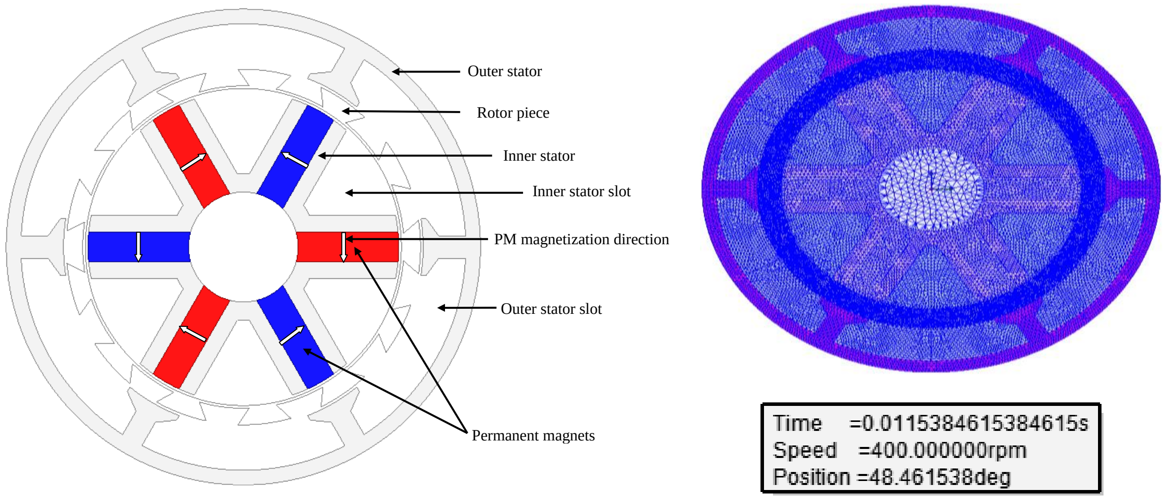
$$L_s = \frac{\psi_s - \psi_{nl}}{I} \tag{1}$$

$$L_m = \frac{\psi_m - \psi_{nl}}{I} \tag{2}$$

where: I is applied phase current amplitude, ψ_m is flux linkage between two phases on load, ψ_s and ψ_{nl} is the phase flux linkage of a particular phase on load and on no-load conditions, respectively (Awah, 2019).

$$L_d = \frac{\psi_d - \psi_{mag}}{i_d} \tag{3}$$

$$L_q = \frac{\psi_q}{i_q} \tag{4}$$



(a) (b)

Figure 1: Model schematic (Awah, 2020)

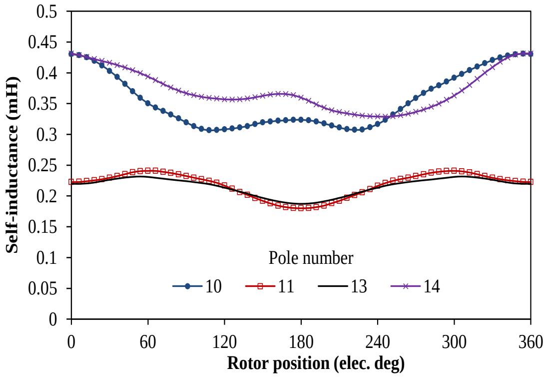
where: ψ_{mag} is magnetic flux linkage, ψ_d and ψ_q are the axis flux linkages, i_d and i_q are the matching axis currents (Awah and Okoro, 2019a).

RESULTS AND DISCUSSION

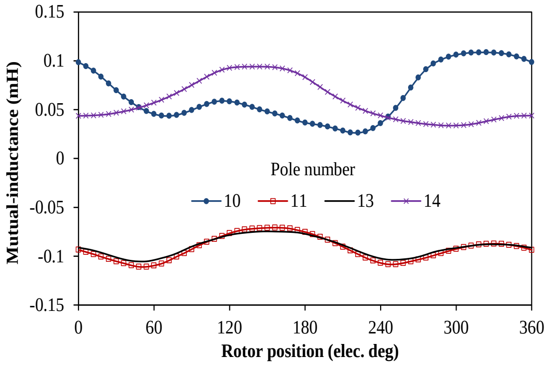
Self-inductance and mutual inductance outlines are presented in Figure 2. It is revealed that the 10-pole and 14-pole machine categories have higher amounts of self and mutual inductances compared to 11-pole and 13-pole equivalents. This higher amount of self-inductance is good fault-tolerance ability (Bianchi *et al.*, 2006) and (Awah *et al.*, 2016); however, a corresponding lower mutual inductance value is required in an ideal situation, for enhanced magnetic decoupling amongst the windings.

The axes' inductance is shown in Figure 3. The 10-pole and 14-pole machine types have a greater value of direct axis inductance; however, with a comparably matched lower amount of quadrature-axis inductance. Machines that exhibit a high amount of direct-axis inductance would be easily susceptible to magnetic saturation (Awah, 2022); this conviction about the inductance-saturation concept is fairly reflected in Table 1 and Figure 4. Predicted inductance values of the analyzed machines are listed in Table 1; fault-tolerance and improved reliability potentials of the machines can be inferred from Table 1, using its inductance ratios. The predicted negative values of mutual inductances in Table 1 indicate that the assumed current directions in the simulations are in reversed order. However, it is important to note that the computed inductance ratios are absolute values, as shown in Table 1. It is worth noting that an electrical machine having a small value of mutual to self-inductance ratio has preferred fault-tolerance and reliability properties, as highlighted in (Zhao *et al.*, 2021) and (Awah, 2024). It is also noticeable that the investigated machines in this study would have negligible reluctance torque, due to practically unity ratios of its axes inductance (Awah and Okoro, 2019b).

It is important to emphasize that the predicted results of this study is computer-generated through finite element analysis software of the designed Figure 1 structure; it is not based on analytical modelling or its associated assumptions. Nevertheless, Parks' transformation technique is also utilized in converting the relevant three-phase components to its equivalent two-axis variables (direct-axis and quadrature-axis components).

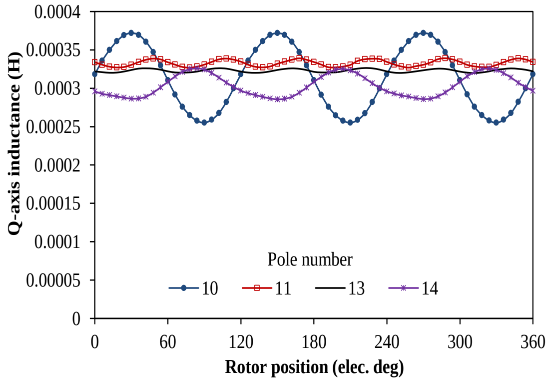


(a) Self-inductance

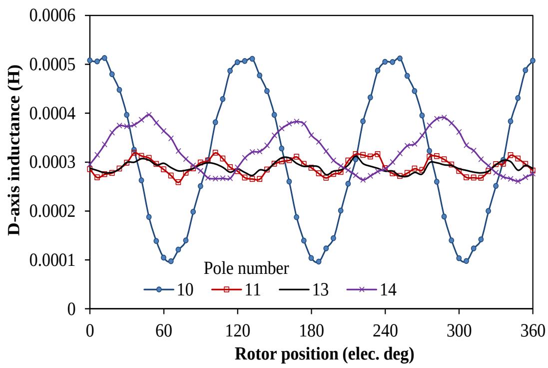


(b) Mutual inductance

Figure 2: Inductance comparisons



(a) Quadrature-axis inductance



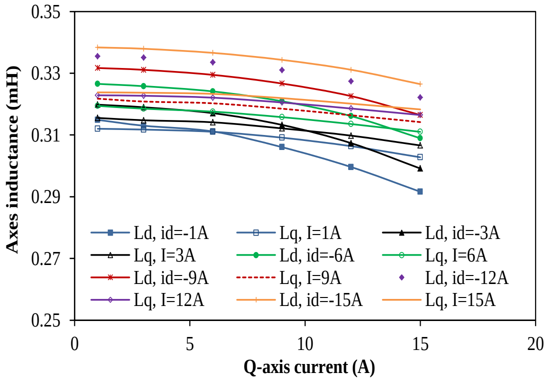
(b) Direct-axis inductance

Figure 3: Axes inductance

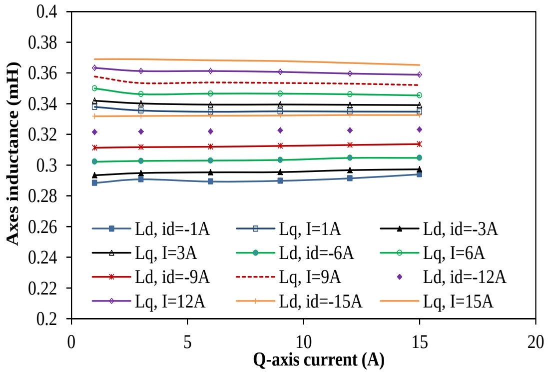
Table 1: Inductance Values

Item	Value			
Pole number	10-pole	11-pole	13-pole	14-pole
Direct-axis inductance (L_d), mH	0.3169	0.2903	0.2892	0.3229
Quadrature-axis inductance (L_q), mH	0.3139	0.3328	0.3230	0.3036
Self-inductance (L_s), mH	0.3556	0.2188	0.2159	0.3727
Mutual inductance (L_m), mH	0.0646	-0.0921	-0.0906	0.0585
Operating speed, rpm	400			
Rated current, A	15			
Ratio, L_q / L_d	0.9905	1.1464	1.1169	0.9402
Ratio, $\left\| L_m / L_s \right\|$	0.1817	0.4209	0.4196	0.1570

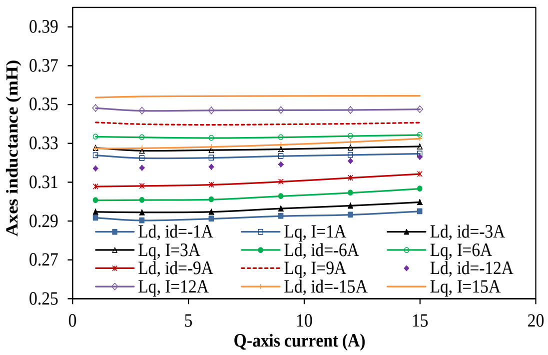
Axes inductance at different current ratings is shown in Figure 4. It is inferred that quadrature-axis inductances are larger than their corresponding direct-axis inductances in the 11-pole and 13-pole categories. However, there are irregular inductance waveform trends in the predicted results of the 10-pole and 14-pole group; likely due to its high harmonic components and or magnetic saturation effects. In particular, the variation of axes inductance with different current settings in the 14-pole configuration has a weird and trivial impact. The rated current of the investigated machine is 15 A, as provided in Table 1. Thus, current ratings below this rated value are applied to avoid the saturation effect due to electric overloads.



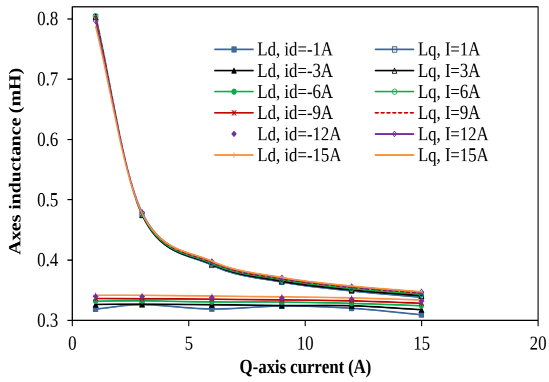
(a) 10-pole



(b) 11-pole

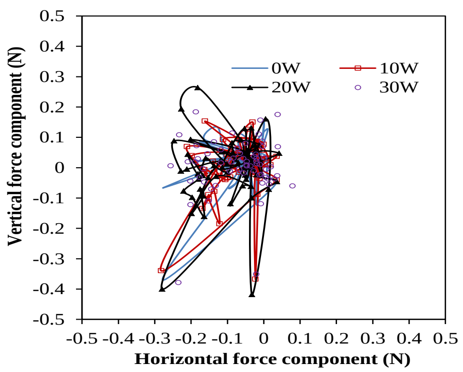


(c) 13-pole

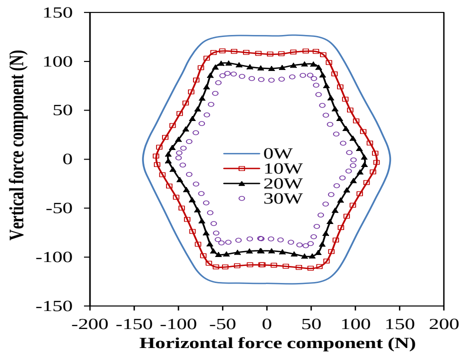


(d) 14-pole

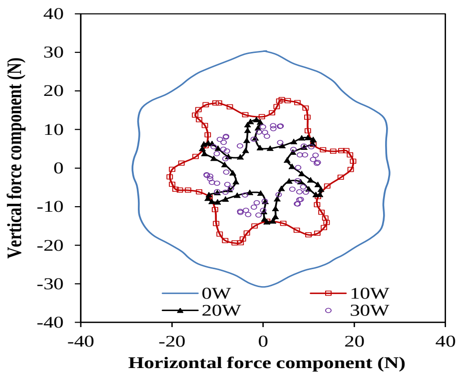
Figure 4: Winding inductances



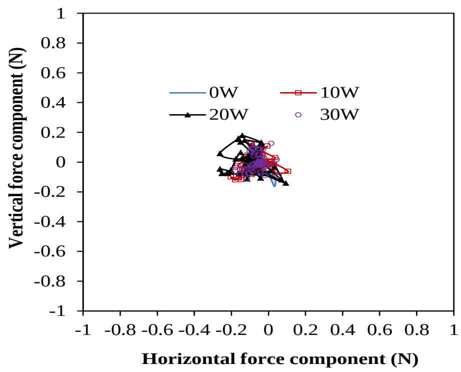
(a) 10-pole



(b) 11-pole



(c) 13-pole



(d) 14-pole

Figure 5: Axes force outlines

Magnetic axes' force components are displayed in Figure 5. It is worth noting that the resulting force components are inversely proportional to the applied load. The 11-pole machine generated the largest force amplitude; nonetheless, this large magnetic force value is a flaw in the electrical machine and its control applications (Oti and Awah, 2022). As usual, the machine category having an even number of poles shows the least and insignificant number of magnetic forces.

CONCLUSIONS

Inductance characteristics of a double stator machine are presented in this study. It is revealed that the machines that have an even number of poles exhibit higher fault-tolerance potential against short-circuit faults compared to the ones that have an odd number of poles; however, with lower ability against magnetic coupling faults, as evident from their various inductance values. 10-pole and 14-pole machine types have lower capacity against magnetic saturation compared to its 11-pole and 13-pole equivalents; though, with desirable lower magnetic force amplitudes. The obtained force values of the compared machine types are inversely proportional to the applied load. Besides, there is an established relationship between the applied current and the resulting axes inductance values for the 11-pole and 13-pole machine categories.

DECLARATION

The authors of this work declare that they have no conflicts of interest.

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