



## IMPACT OF CONDUCTOR SLOTS ON INDUCTANCE AND EFFICIENCY OF A MACHINE

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### ABSTRACT

The number of conductor slot and its winding arrangement would always affect the performance of electric machines; this would include effect on its efficiency and inductance profiles, which is indispensable in the accurate prediction of machine's output values. Similarly, stator and rotor pole selections of PM machines are critical in determining the machine's output performances. Impact of conductor slot number on machine's performance indices such as: cogging torque, flux, inductances and torque ripple of a double stator (DS) machine is researched and presented in this study. The study provides a guide to machine designers and operators on the electromagnetic implications of doubling or halving the slot number of a given electric machine. The compared machine types have six (6) and twelve (12) conductor slots; however, with a fixed pole number of fourteen (14), designated as DS 6-14 and DS 12-14, for the six (6)-slot and twelve (12)-slot machine types respectively. ANSYS/MAXWELL-2D software simulation package is utilized in the entire analyses and it is implemented through finite element analysis method. Predicted torque per magnet volume of the DS 6-14 and DS 12-14 machine types at a copper loss of 30 W is 226.56 kNm/m<sup>3</sup> and 291.62 kNm/m<sup>3</sup> respectively. This implies that it would be more economically viable to manufacture the DS 12-14 machine type than its 6-stator slot counterpart, considering its output torque per magnet volume. It is also revealed that the DS 6-14 configuration has larger inductances and higher quadrature (Q)-axis flux compared to its counterpart, albeit; with higher number of undesirable features such as high cogging torque and torque ripple amplitudes. However, the DS 12-14 machine type exhibits greater value of direct (D)-axis flux compared to its equivalent 6-slot machine, in addition to other advantages.

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### 1.0 Introduction

The number of conductor slot and its winding arrangement would always affect the performance of electric machines; this would include effect on its efficiency and inductance profiles, which is indispensable in the accurate prediction of machine's output values (Akbaba and Dalcali, 2022). Also, stator and rotor pole selections of PM machines are critical in determining the machine's output performances, as established in Zou *et al.* (2017a). More so, generated torque of permanent magnet (PM) machine is dependent upon the relative difference between its axis inductances, i.e. on direct (D)-axis and quadrature (Q)-axis inductances (Kashif and Singh, 2022). The dependence of machine's performance on its axis's inductance is reconfirmed in Hu *et al.* (2020). Hence, the impact of conductor slot number on electromagnetic output of a double stator synchronous machine having inner stator- positioned magnets is investigated and presented in this study. In addition, the resulting inductance of PM machine is also dependent upon its number of phases where higher phase number would yield improved mutual inductance level and consequently, enhanced fault-tolerance

capability (Shao *et al.*, 2016). It is important to note that high amount of self-inductance is good and required in an electric machine in order to sustain its short-circuit fault effects (Bianchi *et al.*, 2006), while low amount of mutual inductance in an electric machine indicates the machine's high ability to resist magnetic coupling fault effects of the windings as implemented by (Awah, 2024).

Similarly, conductor slot angle of a PM synchronous machine would proportionally influence the resulting torque, power factor and winding inductance profiles of the machine, as proved by Waheed and Ro (2020). Apart from the impact of number of conductor slots on machine's output performances, a chosen number of conductor and its consequent winding configuration would indirectly affect its electronic drive system (Uzhegov *et al.*, 2017); thus, adequate consideration is required in selecting the most suitable machine topology, for effective machine yield.

Dual stator PM machine with improved machine performance, owing to introduction of flux barrier mechanism on the rotor is proposed by Fan *et al.* (2020). The proposed dual stator machine in Fan *et al.* (2020) is similar to that analysed in this current investigation; though, with different structural and winding configurations. It is worth noting that an electric machine that has V-positioned magnets on its rotor would outperform its equivalent spoke-positioned type; albeit at higher cost implication, owing to increased usage of magnet material. Cost-savings could be realized from similar kind of double stator machine by utilizing cheaper magnetic materials such as ferrite, as demonstrated by Kim *et al.* (2016); however, at the expense of enhanced output electromagnetic torque. Nevertheless, machines having spoke-shaped magnets are usually preferred to its surface-mounted magnet categories, because of its higher flux-focusing abilities (Zou *et al.*, 2017b). Spoke-positioned magnets are adopted in the stators of this present study.

Deployment of brushless dual stator and dual rotor machine is proved to have better electromagnetic performance amongst other merits than its equivalent dual stator single rotor structure; particularly, reduced cogging torque and torque ripple effects; however, with more complicated mechanical assembly (Ullah *et al.*, 2022). It is worth noting that the developed machine in this present study is typically brushless. In addition, large cogging torque amplitude is not favourable to electromagnetic torque production of any electric machine (Awah *et al.*, 2023). This is because cogging torque depreciates the overall electromagnetic torque output, on summation. Amplitude of cogging torque in an electrical machine is a function of the machine's stator and rotor pole arrangements, as demonstrated by Gao *et al.* (2017). It is worth noting that large value of torque ripple is detrimental to smooth operation of electric machines, as highlighted by Awah *et al.* (2023). Nevertheless, improved magnet utilization as well as reduced undesirable features such cogging torque and torque ripple could be achieved in an electrical machine through proper structural modifications; though, with higher mechanical complexity and cost, as inferred from Niu *et al.* (2019). It is proved that by doubling the stator slot number of an electrical machine, its output performances would be enhanced in favour of the increased stator slot-numbered prototype (He *et al.*, 2019). The findings in He *et al.* (2019) are good testimony to the obtained results of this present investigation. Furthermore, the investigation by Zhang *et al.* (2020) also revealed that a PM machine that is equipped with higher conductor slot number would exhibit larger torque density and slightly better efficiency than its counterpart that has lower number of conductor slots.

Impact of increasing the number of conductor slots on electric machine's output characteristics and profiles is presented in this study in order to guide electric machine designers and practitioners on the significance of doubling or halving stator slot number of a machine on its overall output performance. Thus, it is intended to solve the problem of inappropriate selections and or combinations of conductor slot and pole numbers, for optimal and efficient machine output.

## 2. Materials and Methods

### 2.1 Materials

Finite element computational approach is adopted in the whole analyses using ANSYS/ MAXWELL-2D software. The analysed machine types have the same number of poles with different conductor slot numbers, i.e. six (6) and twelve (12) slots. The machine type having six (6) slots is designated as DS 6-14 while its counterpart that has twelve (12) slots is designated as DS 12-14, where DS stands for double stator. It is worth noting that the investigated machine is a three-phase double stator permanent magnet machine with dual air gap arrangement. It is important to note that double stator electric machines have uncountable number of electromagnetic advantages over its equivalent single stator counterparts. The implemented core, conductor and magnet materials are listed in Table 1. Practically, the pole pieces are held together by steel

material of 0.5 mm width, in order to enhance its mechanical strength. It is worth noting that the predicted results of this study are computer-generated via the applied software, using machine models of Figure 1; however, the graph plotting was done using Microsoft Excel tools during the results' post-processing stage.

**Table 1: Machine Parameters (Awah et al., 2023)**

Item	Value
Machine type	DS 6-14 DS 12-14
Conductor slot number	6 12
Pole number	14
Air-gap, mm	0.5
Stack length, mm	25
Machine radius, mm	45
Core material	Steel
Conductor material	Copper
Type of Magnet	Neodymium
Speed, rpm	400
Current, A	15
Turns number/phase	72

## 2.2 Method

The investigation is conducted at both load and no-load simulation conditions. The comparison is done under the same simulation conditions, as could be inferred from Table 1. Transient solver of the implemented software is applied, owing to its high precision potential in predicting time-stepping electromagnetic problems, as highlighted in Awah (2022); as well as its uniqueness in solving speed-varying and position-related magnetic and electric field issues. The direct ( $D$ )-axis and quadrature ( $Q$ )-axis inductances are predicted using Eq. (1) and Eq. (2) respectively (Awah, 2024). More so, the axes inductance is converted from its three-phase variables to two-axis components by utilizing the conventional Parks' transformation method.

The torque ripple ( $T_r$ ) is predicted using Eq. (3) (Oti and Awah, 2022).

$$L_D = \frac{\psi_D - \psi_{nl}}{I_D} \quad (1)$$

$$L_Q = \frac{\psi_Q - \psi_{nl}}{I_Q} \quad (2)$$

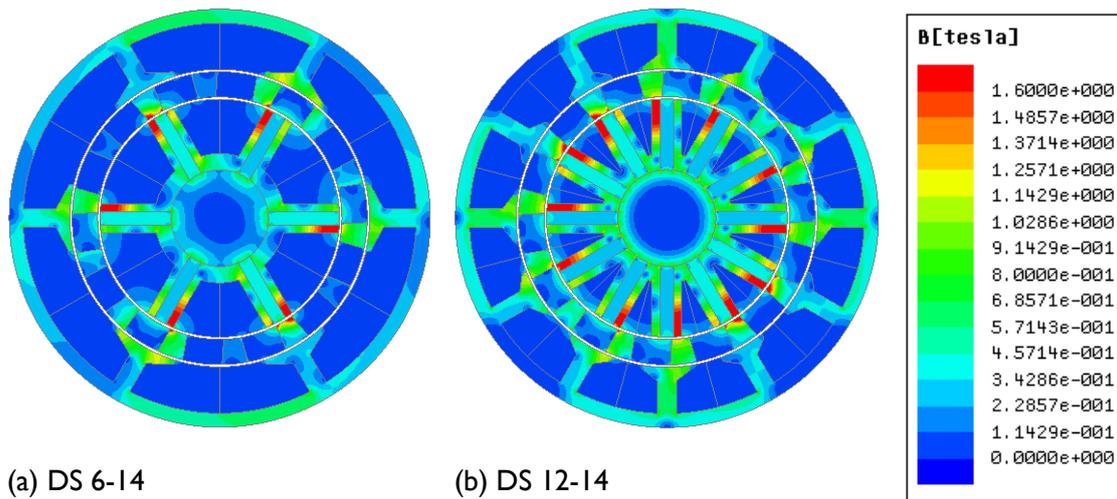
where:  $L_D$  and  $L_Q$  are the direct-axis and quadrature-axis inductances,  $I_D$  and  $I_Q$  are the corresponding axes current,  $\psi_{nl}$  is the no-load flux.

$$T_r = \frac{T_{max} - T_{min}}{T_{av}} \quad (3)$$

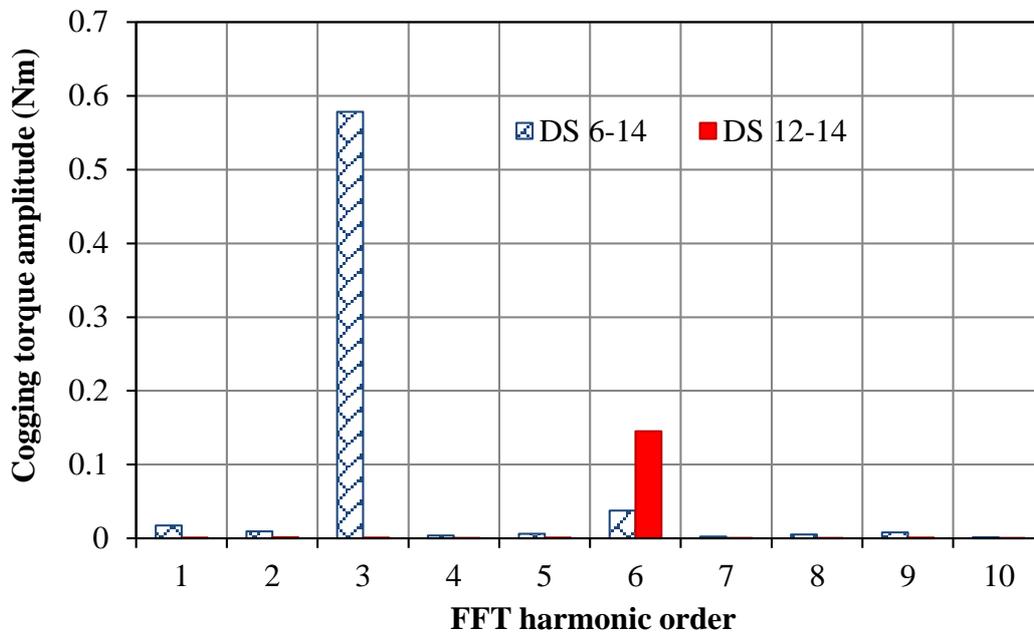
where:  $T_{max}$ ,  $T_{min}$  and  $T_{av}$  is the maximum, minimum and average torque, respectively.

### 3. Results and Discussion

Figure 1 shows the flux density outlines of the investigated machine topologies. It is evident that the inner stator tooth of the compared machine types has higher sensitivity to flux density compared to its other parts. This high sensitivity response is followed by the machine’s rotational parts, as could be seen from Figure 1. Similarly, no-load or cogging torque magnitude of the compared machine types is shown in Figure 2. It is obvious that DS 6-14 machine exhibits larger cogging torque than its equivalent DS 12-14 machine. It is important to keep the cogging torque magnitudes of a machine to its barest minimum value for improved output torque.



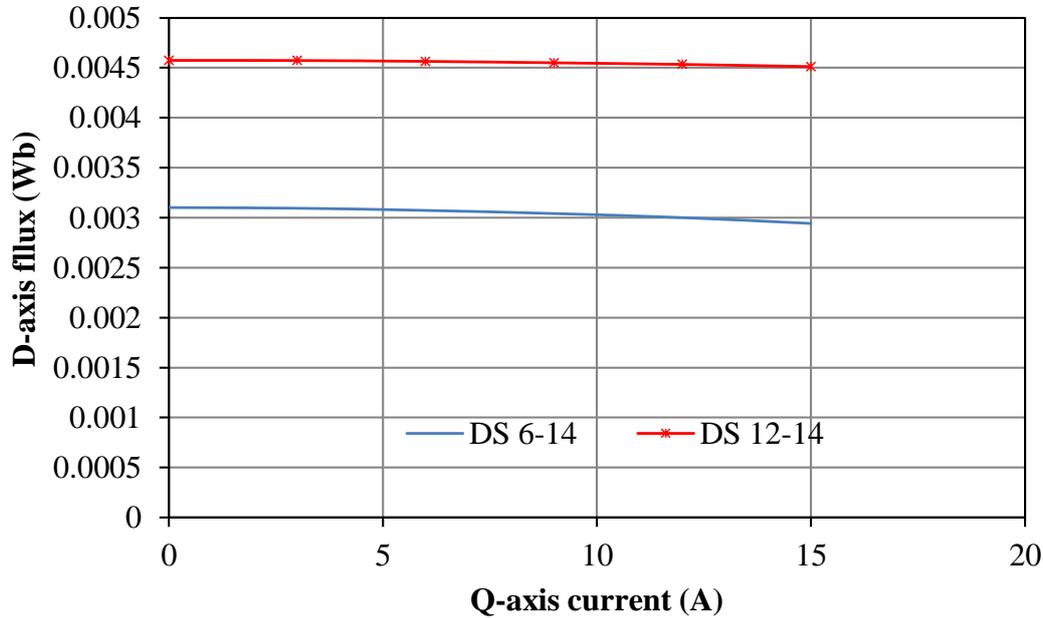
**Figure 1:** Flux density of the investigated machines on no-load



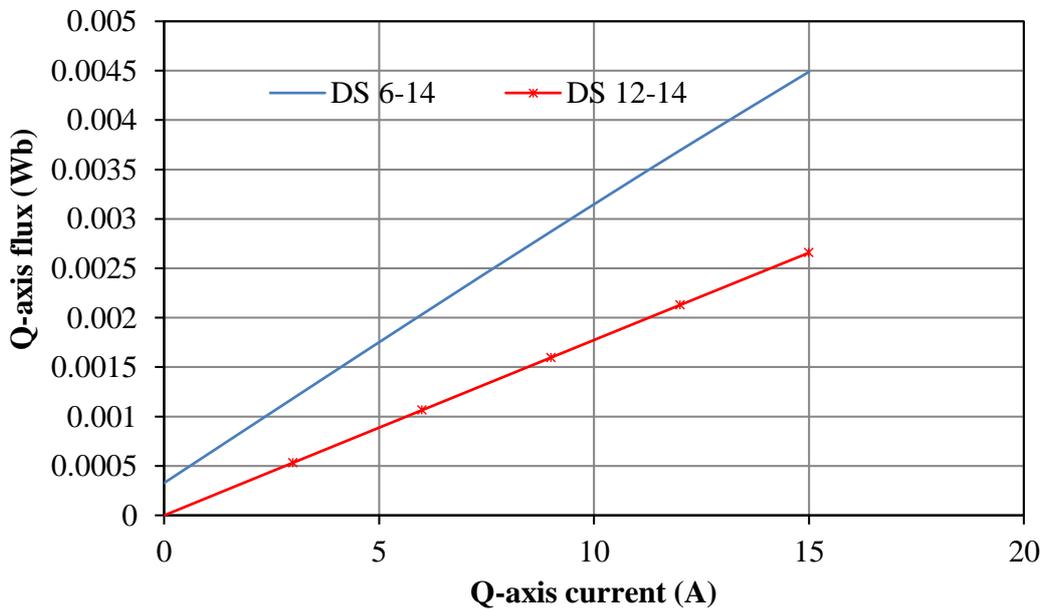
**Figure 2:** Cogging torque

The axes flux of the compared machine types at different quadrature-axis current ratings is depicted in Figure 3. It is revealed that DS 6-14 machine has lower direct ( $D$ )-axis flux but higher quadrature ( $Q$ )-axis flux compared to DS 12-14 machine type. Direct-axis flux is almost insignificant with changes in applied axis current as shown in Figure 3(a). Meanwhile, the quadrature-axis flux varies proportionally with applied axes current as presented in Figure 3(b). Furthermore, the compared machine’s axes inductance is presented in Figure 4.

Clearly, DS 6-14 machine category has higher direct- and quadrature-axis inductances compared to its counterpart, over different rotational positions of the rotor. The direct-axis of a machine is more or less aligned to its rotor initial position direction. Moreover, the amount of *D*-axis flux would invariably influence its overall output torque, as could be inferred from the larger torque per magnet volume of the DS 12-14 machine type, shown in Figure 6 (b).

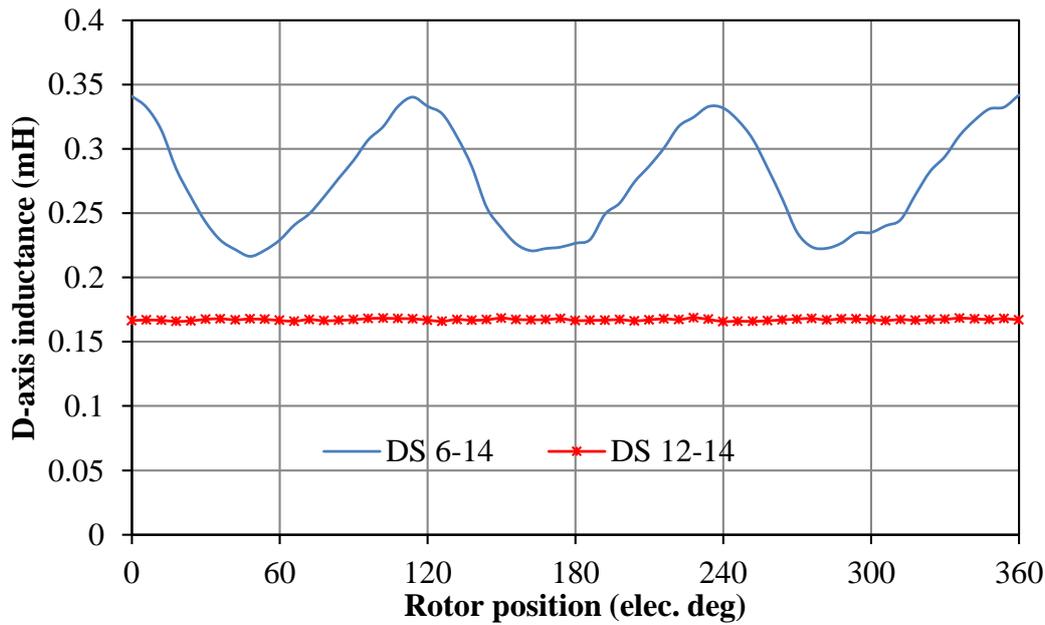


(a) Direct-axis

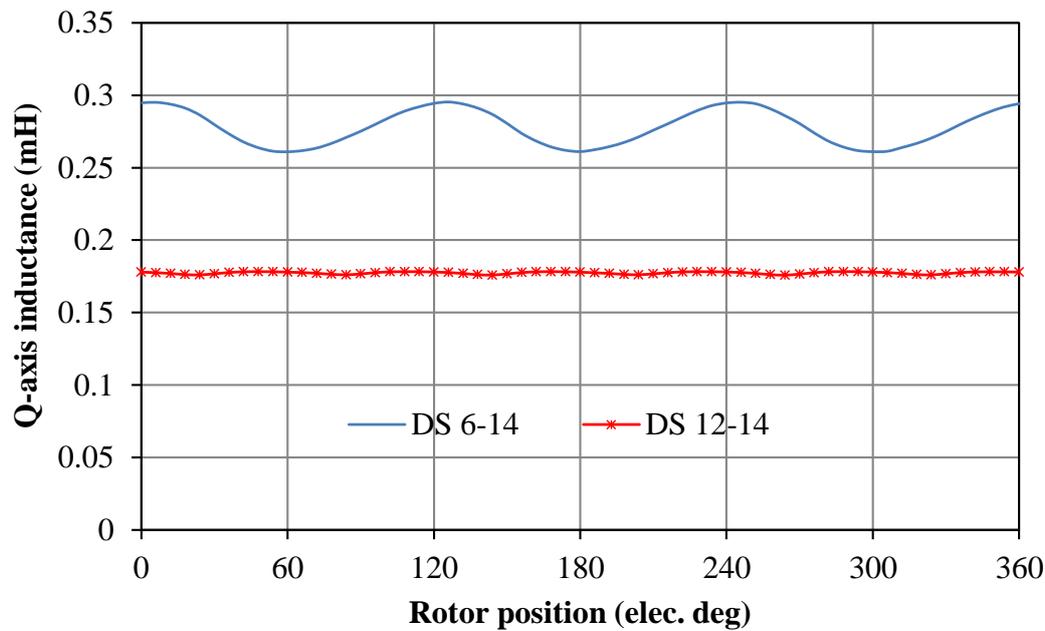


(b) Quadrature-axis flux

**Figure 3:** Axis flux variations with current



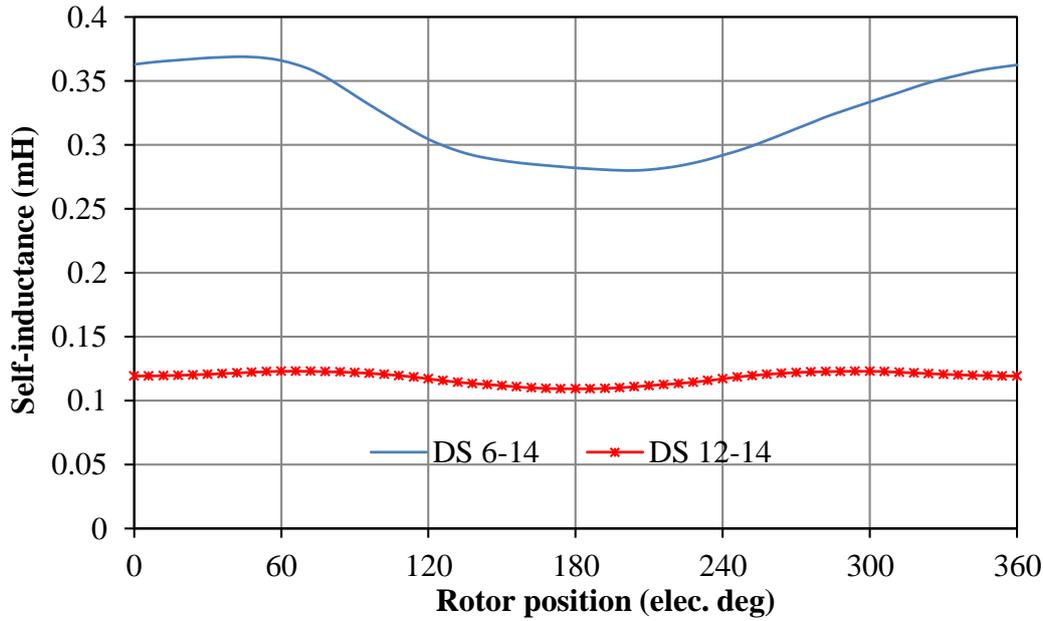
(a) Direct-axis inductance



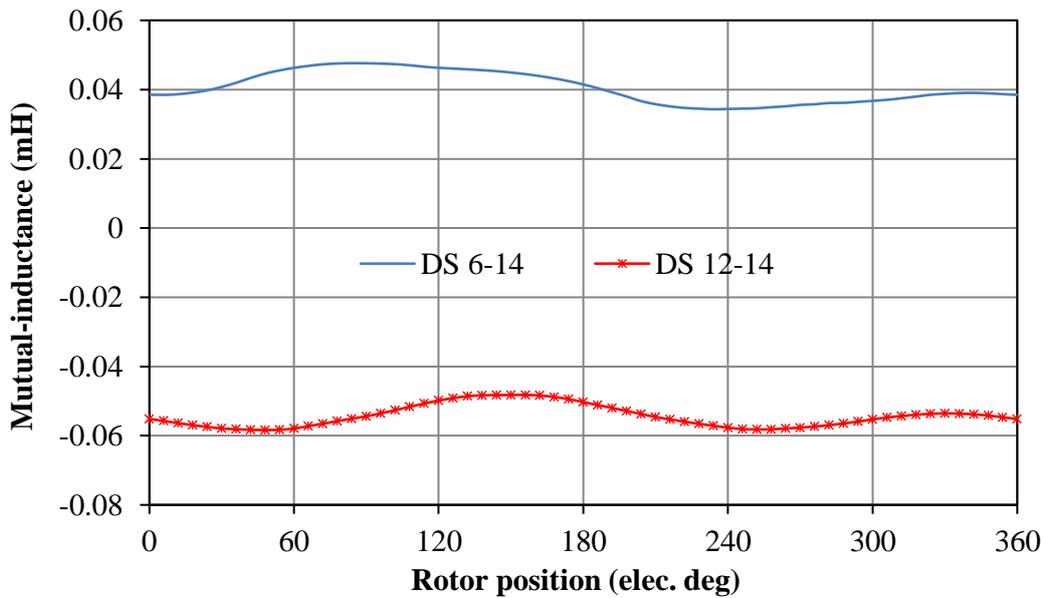
(b) Quadrature-axis inductance

**Figure 4:** Axis inductances

Finite element predicted self and mutual inductances of the investigated machine types are presented in Figure 5. It is worth revealing that the DS 6-14 machine topology has both higher self and mutual inductances compared to the DS 12-14 machine equivalent. Since, the DS 6-14 machine type has larger amount of self-inductance; then, it would invariably exhibit higher fault-tolerance potential over short-circuit faults; though, with a drawback on its magnetic isolation potential, owing to its high possession of absolute mutual inductance value.



(a) Self-inductance

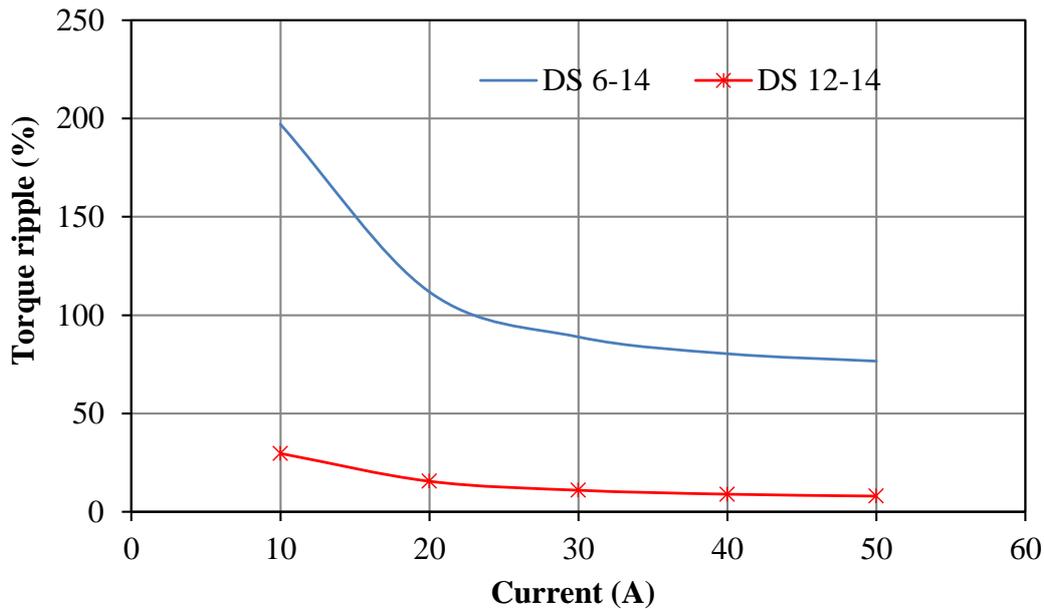


(b) Mutual-inductance

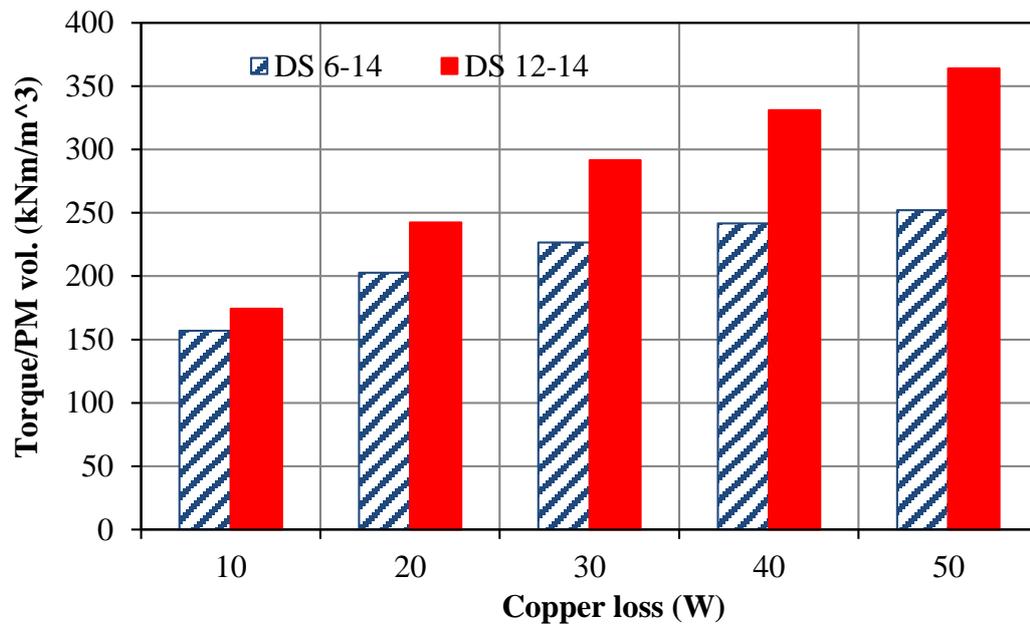
**Figure 5.** Winding inductances

Torque ripple profiles of the two analysed machine types are compared in Figure 6(a). A wide gap exists between the predicted torque ripple values of the compared machine configurations, the minimum value being recorded in the machine type with larger conductor slot number. Large amount of torque ripple/pulsation is not amenable to smooth control of machines. Torque per applied magnet volume difference between DS 6-14 and DS 12-14 machine types is at least over 10 % in all the simulated load settings. This difference tends to increase with increasing loading conditions, as shown in Figure 6(b).

It is important to note that supplied current has great effect on the resulting output characteristics of any given electric machine; particularly, at electromagnetic saturation conditions.



(a) Torque ripple



(b) Torque per magnet volume

**Figure 6.** Torque ripple and torque per magnet volume

#### 4. Conclusion

The impact of number of conductor slots on performance of a double stator electric machine is presented in this study. The investigation shows that larger machine inductances are provided by the machine type that has lesser conductor slot number, i.e. by DS 6-14 machine topology, because the DS 6-14 machine type would have higher susceptibility to magnetic saturation, owing to the direct relationship between a machine's inductance value and its corresponding saturation impacts. Nevertheless, DS 6-14 machine type exhibits high cogging torque and torque ripple values, which are demerits. The predicted torque per magnet volume of DS 12-14 machine type at rated speed outweighs that of its equivalent DS 6-14 topology, by over 10 % at all electromagnetic load settings. Thus, by doubling the stator slot number of the investigated machine, its output torque is enhanced; in addition to a consequent high prospective of the machine's cost-effectiveness over the DS 6-14 machine type.

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