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Evaluation of the Effect of Doubling the Stator Slot Number of a Permanent Magnet Machine

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ABSTRACT

The slot numbers of an electric machine play an important role in the machine's output performance(s). Thus, the significance of doubling stator slot number of a Double Stator (DS) Permanent Magnet Machine (PMM) is presented in this study; to evaluate its impact on the overall electromechanical output of the considered machine and for better guide on appropriate slot-pole number combinations of the chosen machine type. The number of slots considered is six (6) slots and its corresponding binary is taken to be twelve (12). The machine indices comprise: flux linkage, induced voltage, torque, loss, power, and efficiency. Finite Element Analysis (FEA) is implemented in this investigation using MAXWELL-2D software. The study shows that the 12-slot machine configuration has higher flux linkage, induced voltage, power, and torque values compared to its equivalent 6-slot machine. The predicted shaft torque and power of the 6-slot machine are 0.93 Nm and 353.5 W, respectively, while the corresponding values obtained for 12 slots are 1.42 Nm and 491.3 W. However, greater electromagnetic loss and consequent lower efficiency are obtained from the 12-slot machine type, coupled with high usage of magnetic materials and likely higher cost consequences. The investigated machine is suitable for in-wheel traction applications.

INTRODUCTION

Stator slot numbers and their matching pole numbers are vital in determining the electrical machine's generated outputs (Gao *et al*., 2017) and (Wang *et al*., 2022). The effectiveness of doubling the stator slot number of an electric machine on its electromagnetic output is confirmed by Kouhshahi *et al*. (2020) with the drawback of high torque ripple characteristics. In addition, harmonic amplitudes of the voltage are significantly reduced by doubling the stator slot of a machine (Jung *et al*., 2021); consequently, the magnetomotive force of the machine is reasonably affected (Imamura and Lorenz, 2020). Thus, the significance of doubling the stator slot number of a double stator machine is investigated in this study, for a better guide on slot and pole number selections/combinations of the machine. It is established by Anvari *et al*. (2018) that by simultaneously doubling the pole and its stator slot numbers of a Permanent Magnet Machine (PMM); then, its average torque would be improved. Also, a linear relationship is established between the increasing pole/stator slot numbers and the resulting output torque. Similarly, the investigation by Fu *et al*. (2023) revealed that by increasing the stator teeth number of a machine, its electromotive force naturally improved. Besides, the magnitude of unwanted machine outputs like rotor magnetic force and its associated effects such as noise and vibration are inversely influenced by combining the appropriate slot and pole numbers of the machine (Zhang *et al*., 2018).

More so, implemented slot and pole number configurations of a machine would customarily affect the machine's winding factor (Xie et al., 2019) and consequently its resulting output performance (Awah et al., 2023a). In contrast, the study by (Huang et al., 2019) revealed that a variable flux electric machine having a lower slot number would produce relatively larger output torque than its equivalent higher slot-numbered machine; however, this notion is dependent upon the relative difference between the integral values of stator slot and pole numbers, of the machine in question. The smaller the difference between the slot and pole numbers; then, the higher its resulting output torque. Nonetheless, the machine with a higher number of slots is preferred due to its better heat management and improved overload potential. It is worth stating that the considered case scenario in (Huang et al., 2019) has both its stator and rotor pole numbers synchronously doubled at once.

Again, higher torque density is be achieved from a machine by increasing both its slot and pole numbers (Carraro et al., 2018); however, usually with a detrimental effect of lower saliency ratio and consequential poor magnetic field-weakening ability. In principle, the significance of doubling the stator slot number of an electrical machine is studied and compared in this current investigation, in order to provide adequate guide on slot and pole number fusions, for productive electromagnetic and electromechanical outputs

MATERIALS AND METHODS

Figure 1 depicts the two-dimensional structural schematics of the developed double stator machine types, having 6-stator slots and 12-stator slots, respectively. The analyzed machine basics and values are listed in Table 1.

Table 1: Machine basics and values

Item	Value
Rated current	15 A
Poles	14
Air gap size	0.5 mm
Machine active length	25 mm
Stator diameter	90 mm
Stator and rotor core material	Steel
Coil material	Copper
Magnet	Rare-earth
Speed	400 rpm

It is worth mentioning that the analyses of the two machine types are conducted under the same simulation condition, for fairness. For instance, both machine types have the same number of turns and the same overall machine outer diameter. Nevertheless, a larger amount of magnet is utilized in the 12-slot machine and this could translate into possible higher cost implications; owing, to the scarcity of rare-earth magnetic materials and its monopolized market structure. Finite Element Analysis (FEA) is implemented in this investigation using MAXWELL-2D software. The analyses are conducted on open circuit, as well as on electric and magnetic load conditions. The applied magnet material is neodymium-iron-boron (Nd-Fe-B). It is worth noting that single-tooth concentrated winding is utilized in the analyses. The torque/power–speed curves are obtained by applying a negative direct-axis current to weaken the magnetic fields or fluxes. It is important to note that the speed regions of the curves could be extended through the use of mechanical flux adjusters, as demonstrated in (Zhao et al., 2023); although, the use of mechanical adjusters in widening the speed range is not considered in this study.

The mathematical relationship between the induced voltage (E) and flux linkage (ψ) of the analyzed machine is given in Equation (1) by (Jung *et al.*, 2023), as a change of flux rate function.

$$E = -N\frac{\Delta\psi}{\Delta t} \tag{1}$$

Where: Δ is change, N is the number of turns and t is time.

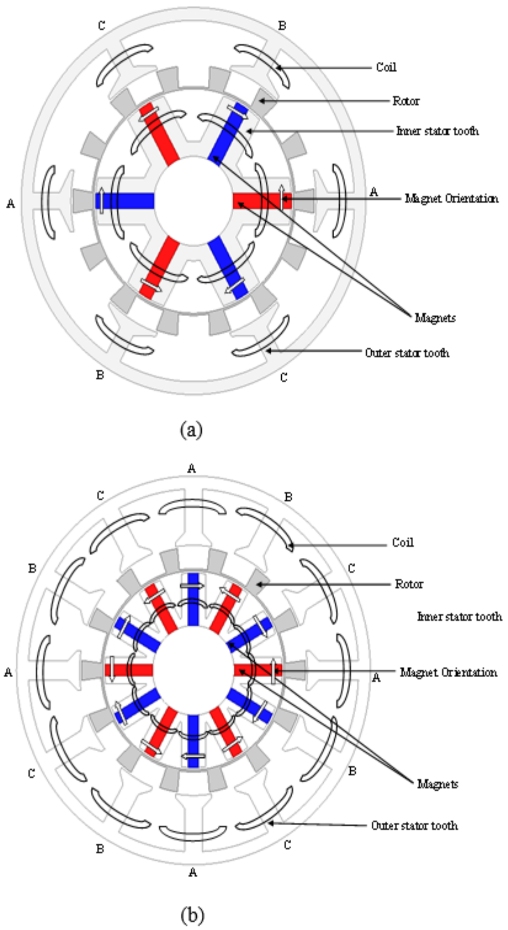


Figure 1: Investigated machine models (Awah *et al.*, 2023b) (a) 6-stator slot; (b) 12-stator slot

The calculated shaft power (P) and torque (T) values are predicted using Equation (2) and Equation (3), respectively, in (Awah *et al.*, 2019) and (Chen and Zhu, 2008). The predicted core loss (W_{core}) value of the machine is calculated using Equation (4) in Awah (2022). The resulting efficiency (η) is predicted with Equation (5) in (Awah, 2022). However, the friction loss (W_f) and windage loss (W_d) are neglected in this investigation.

$$P = \omega T \tag{2}$$

Where: ω is motor rotational speed, T and P are the shaft output torque and power, respectively.

$$T = \frac{3}{2}N_r\psi_{PM}I_q \tag{3}$$

Where: N_r is pole number, ψ_{PM} is magnet flux and I_q is quadrature-axis current.

$$W_{core} = k_h B_m^2 f + k_e\left(B_m f\right)^{3/2} + k_c\left(B_m f\right)^2 \tag{4}$$

Where: k_h, k_e, and k_c are the hysteresis, excess, and eddy current loss constant, respectively; f is frequency and B_m is the peak flux density.

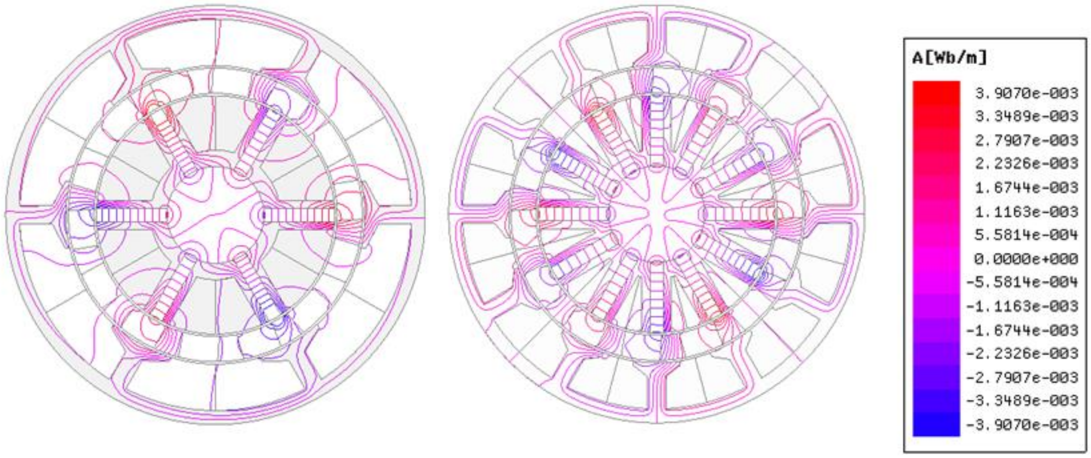
$$\eta = \frac{P}{P + W_{core} + W_{PM} + W_{copper} + W_f + W_d} \times 100\% \tag{5}$$

Where: P is output power; W_{core}, W_{PM}, and W_{copper} are the core, magnet eddy current, and copper loss, respectively.

RESULTS AND DISCUSSION

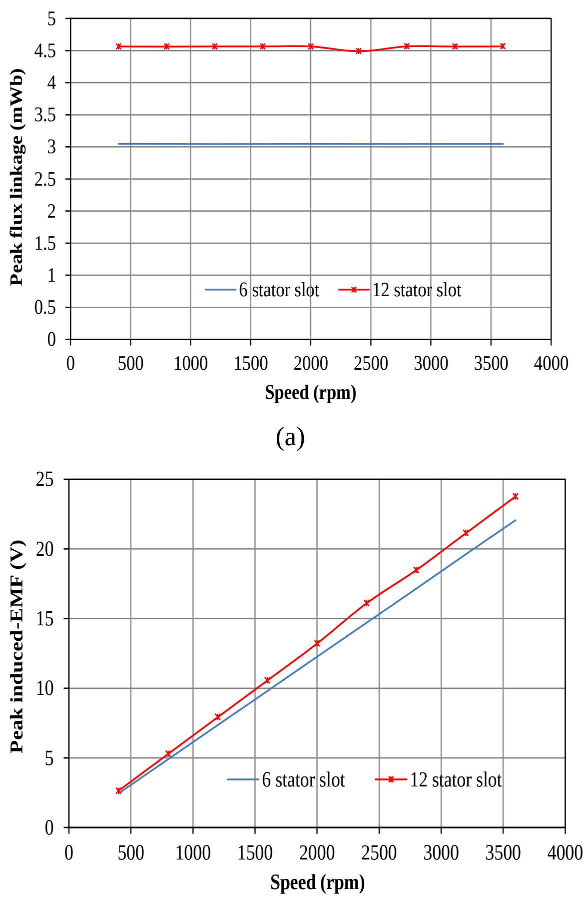
Magnetic flux lines of the investigated machine on open-circuit conditions are presented in Figure 2. The 12-slot machine type seems to possess larger flux lines than the 6-slot topology. This high flux distribution attribute is reflected in the flux linkage magnitude of the 12-slot machine, given in Figure 3 (a). This trend is persistent in the generated induced-voltage or induced-electromotive force (EMF), as shown in Figure 3(b). Recall from Equation (1) that

EMF is the rate of change of flux over time. It is obvious from Figure 3 that both flux linkage and induced-voltage of a machine is directly related to the machine's applied



(a) (b)

Figure 2: Flux lines on open circuit (a) 6-stator slot; (b) 12-stator slot



(a)

(b)

Figure 3: Flux linkage and induced voltage (a) Flux linkage versus speed; (b) Induced voltage versus speed

speed. Meanwhile, the air gap flux density outlines of the compared machine categories at different rotor locations are depicted in Figure 4.

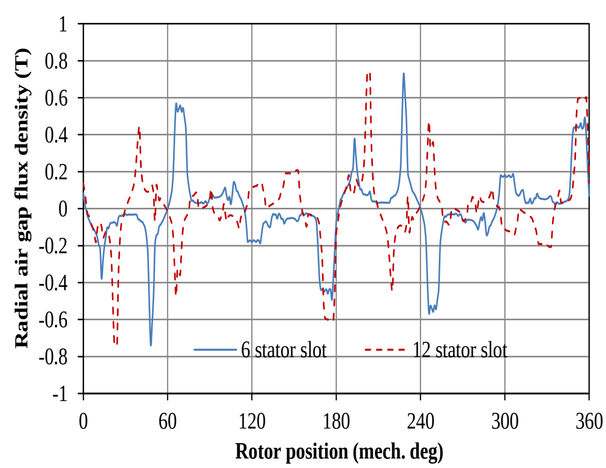
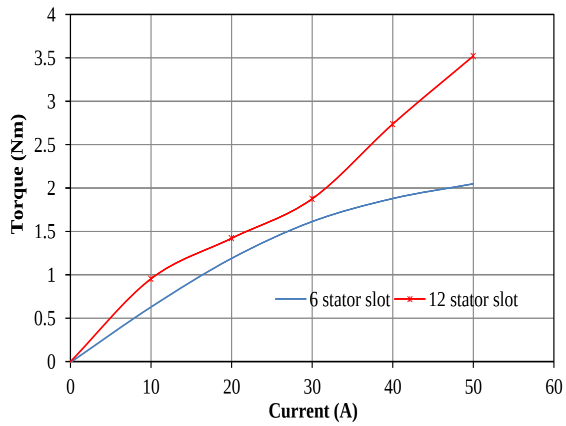
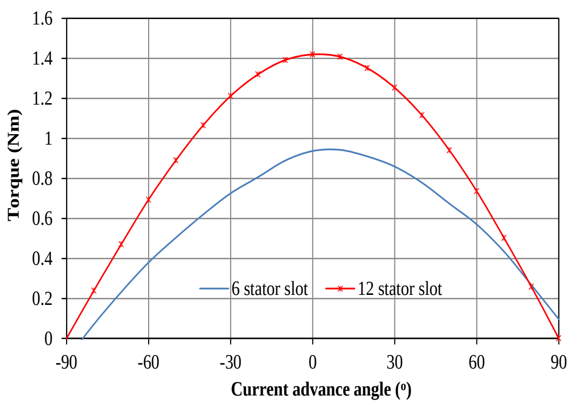


Figure 4: Air gap flux density

The average torque variations with current and current angle are presented in Figure 5. In both situations, the 12-slot machine type exhibits greater torque value. It is also noticeable from Figure 5(a) that there is a remarkable difference between the compared machine categories at about twice its rated current value and above i.e. from 30 A upwards; likely, due to the influence of magnetic saturation.



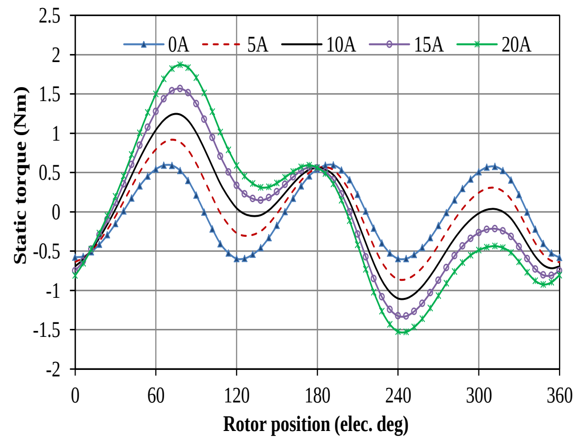
(a)



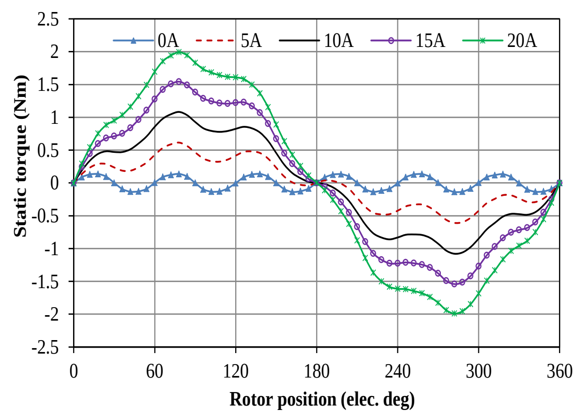
(b)

Figure 5: Average torque (a) Torque versus current; (b) Torque versus current angle

Figure 6 shows the static torque outlines of the compared machine types. It could be seen that the 12-slot machine has a more symmetric outline as well as a higher static torque value than its equivalent 6-slot machine. In Figures 6(a) and 6(b), the resulting static torque amplitudes are seen to have direct proportionality with the applied current. Similarly, the obtained shaft torques of the two analyzed machines are shown in Figure 7. Again, greater torque is generated by the 12-slot machine type; however, the 6-slot machine has a larger capacity to operate in an extended speed region. This wider speed rangeability is an excellent and required machine attribute in traction and vehicle applications, as highlighted in (Xu and Wang, 2023). It is observed that both machine types have negligible reluctance torque and dominating magnetic torque profiles.



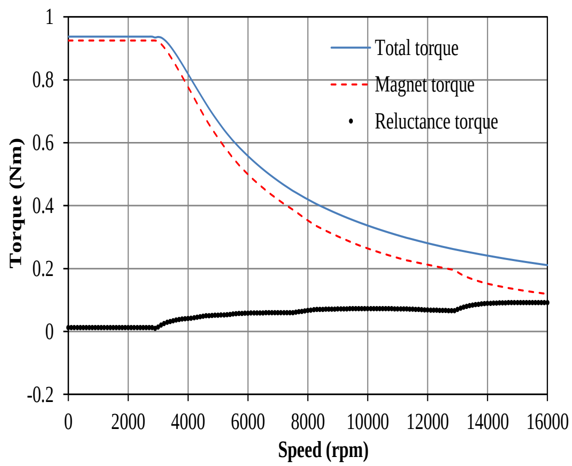
(a)



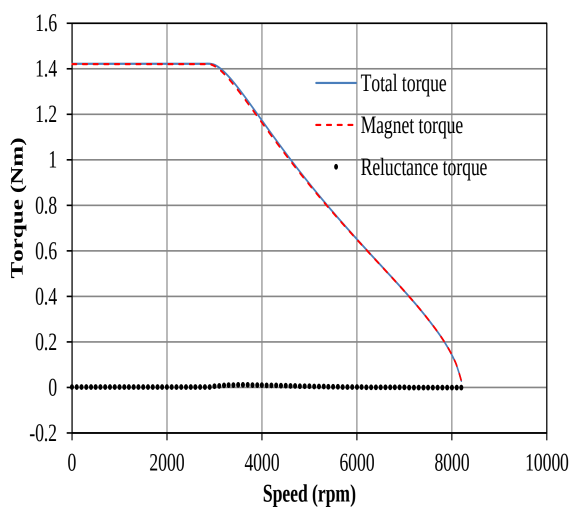
(b)

Figure 6: Static torque versus rotor position (a) 6-stator slot; (b) 12-stator slot

The generated shaft power is depicted in Figure 8 (a). Although, the 12-slot machine has a larger power value; the 6-slot machine type has enhanced flux-weakening potential in the constant power region and would invariably have a larger amount of self-inductance value, as pointed out by (Zhang *et al.*, 2018). Nevertheless, the 6-slot machine type exhibits a higher value of total harmonic distortion (THD) of the voltage, as shown in Figure 8(b); which is a flaw in motor drive applications (Oti and Awah, 2022).



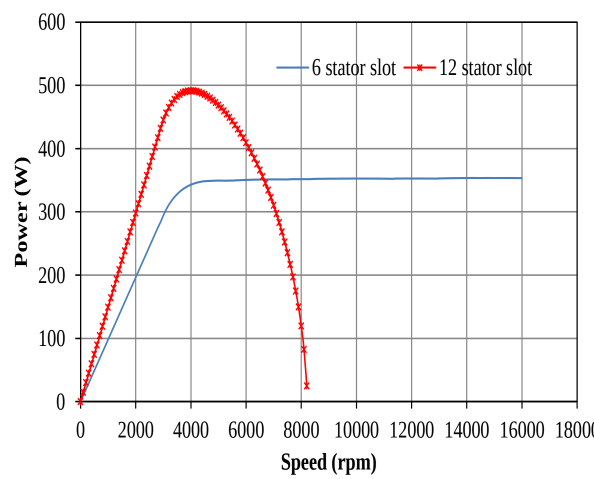
(a)



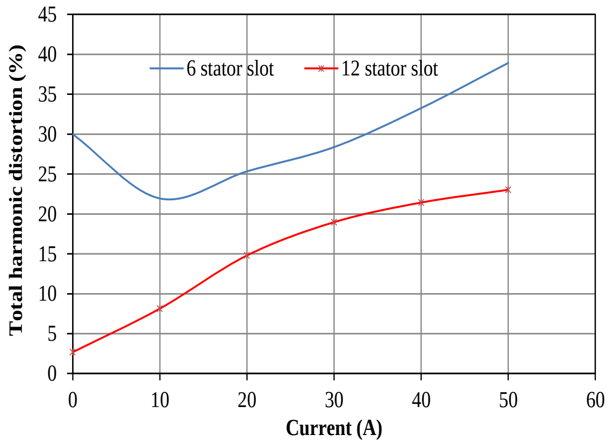
(b)

Figure 7: Shaft torque versus speed (a) 6-stator slot; (b) 12-stator slot

The loss and efficiency characteristics of the two machine types are displayed in Figure 9. The flux density contours of the machines are presented in Figure 9 (a) and (b). The 6-slot machine type is more liable to saturation effects than its counterpart, as can be inferred from Figure 9(a) and (b). Predicted FEA total loss is simulated at rated current and speed of 15 A and 400 rpm, respectively. Unfortunately, the 12-slot machine has a higher overall loss value and consequently lower efficiency than its equivalent 6-slot machine type. Nevertheless, electric machine loss and efficiency value could be reduced and improved, respectively by adopting relevant core and coil materials, as presented in (Palangar and Soong, 2022). Additionally, the core loss components could be reduced further through the segmentation process; although, with a deteriorating effect on the applied material contents and features (Garmut and Petrun, 2022). More so, magnet segmentation is capable of reducing eddy current loss in an electric device, as highlighted in (Awah, 2022). The loss and efficiency values of the investigated machine topologies are compared in Figure 9 (c) and (d).



(a)



(b)

Figure 8: Shaft power versus speed and THD (a) Power versus speed; (b) THD versus current

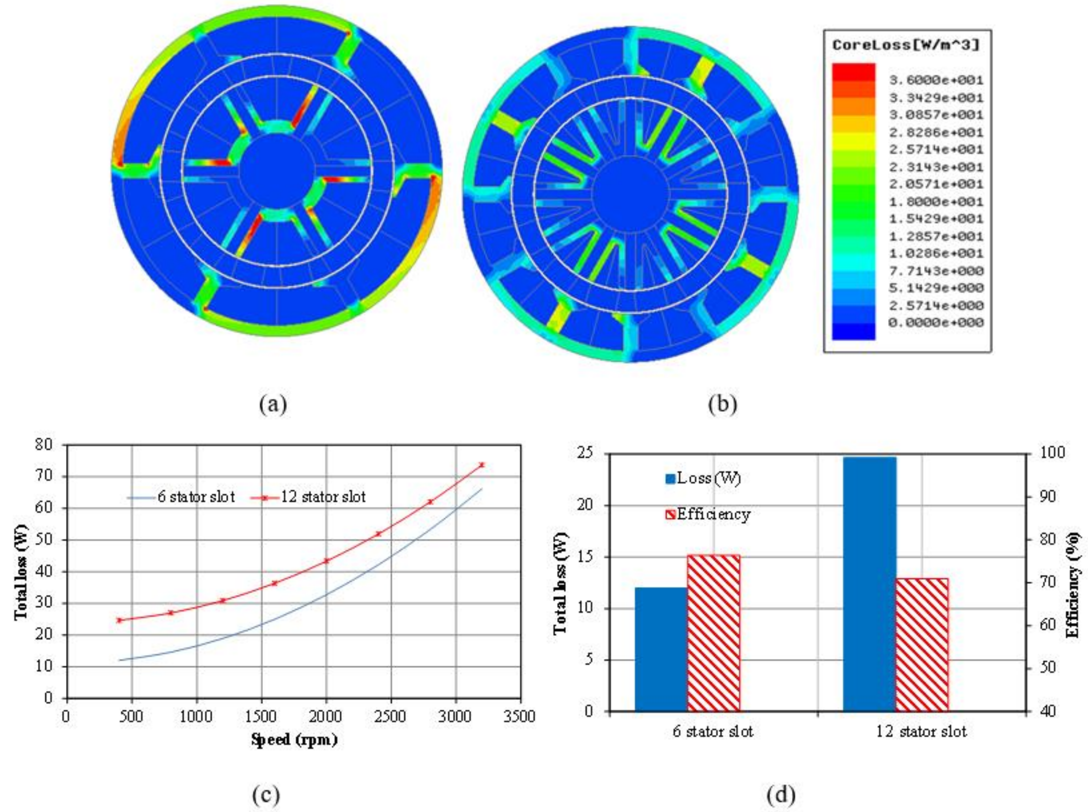


Figure 9: Loss and efficiency comparisons (a) 6-stator slot; (b) 12-stator slot; (c) Total loss; (d) Loss and efficiency

CONCLUSION

The significance of doubling the stator slot number of a double-stator electric machine is analyzed and presented in this study. The analyses show that larger values of electromagnetic and electromechanical performances such as induced voltage, flux linkage, torque, and power of the investigated machine categories are produced from the 12-slot machine type compared to its 6-slot counterpart. The average shaft torque of the 6-slot and 12-slot machine types at rated current is 0.93 Nm and 1.42 Nm, respectively. More so, the 6-slot machine type exhibits a higher amount of total harmonic distortion, which is an additional demerit. Nevertheless, the enhanced performances of the 12-slot machine type are however saddled with increased electromagnetic loss, which is an undesirable machine feature plus its potentially higher cost implication. The predicted efficiency of 6-stator slot and 12-stator slot machine category 76.4 % and 71.0 %, respectively.

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