

PAPER 18 – INFLUENCE OF STATOR SLOT NUMBER ON THE PERFORMANCE OF AN ELECTRICAL MACHINE

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ABSTRACT

The influence of stator slot number on the performance of a given double stator permanent magnet machine was investigated in this study. The considered permanent magnet (PM) machines are classified as: Type I and Type II, having 6 stator slots and 12 stator slots, respectively. Finite element analysis (FEA) is adopted in the result estimations. It is observed that an increase in the number of stator slots result to enhanced machine performances such as: higher induced voltage and torque outputs. Torque pulsations in the machine are significantly reduced by doubling the slot number; this reduction is in the ratio of 6:1, for the Type I and Type II machines. Nevertheless, Type I machine has higher machine efficiency at low operating speed than its Type II counterpart. Additionally, Type I machine exhibits superior speed range than Type II machine. The investigated machine types would be suitable in low speed direct-drive applications. By doubling the slot number of the analyzed machine from six (6) to twelve (12), its output torque and induced voltage increased by 34.5 % and 31.7 %, respectively, at rated speed and load conditions. Consequently, output power of the machine also increased by 36.4 %.

KEYWORDS: Concentrated windings, Double stator, Efficiency, Loss, Slot number, Torque.

1. INTRODUCTION

The stator slot number of a given electrical machine is vital in predicting the output performance of the machine. Wang *et al*, (2008) clearly stated that slot number and pole number grouping of an electric machine would greatly influence its output performance, particularly the resulting winding factors. If the slot number of a given permanent magnet (PM) machine is doubled; then, the resulting magnetomotive force (MMF), electromotive force (EMF) and average torque values of the machine would be enhanced correspondingly, as established in (Wang *et al*, 2014a). In contrast, the resulting outcome of doubling the stator slot number of a particular machine would be a function of the machine's level of flux-leakage and fringing effects, coupled with the kind of machine configuration (Zhang *et al*, 2009). The impact level of this slot number difference on the overall electromagnetic performance of a given double stator permanent magnet (DSPM) machine is considered and presented in this current study.

The studies in Xu *et al*, (2010) and Zhang *et al*, (2012) reveal that if the ratio of pole to slot number of flux-switching permanent magnet (FSPM) machine is decreased by half i.e. a concurrent reduction in both the machine's pole and slot number; then, there would be a corresponding higher average torque, lower torque ripple, enlarged magnetic flux density, improved efficiency and increased self-inductance value; however, with consequent reduction on the machine's field-weakening potential. Additionally, the generated flux-linkage value of the machine with reduced pole to slot ratio would be significantly increased, as presented in Tang *et al*, (2013).

The investigated machine types in this current study have double stator and double air gap structures, owing to the usual merits of double stator electrical machines over the single stator ones, as highlighted and proved in Jiang *et al*, (2021) and Zhao *et al*, (2022). These numerous advantages of double airgap and double stator machine are re-emphasized in Ding *et al*, (2023). Nevertheless, the investigation in Ullah *et al*, (2022) reveal that double rotor machines can outperform its double stator equivalents; however, with increased manufacturing complexity and higher electromagnetic losses. Moreover, Su *et al*, (2018) showed that when magnets are mounted on the rotor of FSPM machine, it would produce superior electromagnetic performance(s), in addition to better thermal management capacity (Zhang *et al*, 2009) than its equivalent stator mounted magnet counterpart; though, with inferior overall machine efficiency.

Wang *et al*, (2014b) proved that the iron loss value of a PM machine would increase if its slot number is doubled; however, with a resultant decrease in eddy loss value. The obtained loss results in Wang *et al*, (2014b) are in consonant

with the predicted loss values in this present investigation, shown in the last part of Section 3 of this study. Furthermore, the amount of unbalanced magnetic force on the rotor of a given machine would also largely depend on its slot and pole number arrangement, as proved in Zhu *et al.*, (2013).

Essentially, effect of doubling the stator slot number on the overall performance of a given double stator electric machine is analyzed and presented in this current investigation. The background of study with its relevant literature is presented in Introduction, the adopted method and materials are presented in Section 2 of this study, the predicted results and conclusion are provided in Section 3 and Section 4, respectively.

2. MATERIALS AND METHODS

Predicted results in this study are estimated using finite element analysis (FEA) approach; MAXWELL-2D software is applied in this analysis. The considered machines are classified as: Type I and Type II, having six (6) stator slots and twelve (12) stator slots, respectively with each in either of the two stator parts (inner and outer stators). The coils of both inner and outer stator slots are joined in series for improved overall performance, in each of the machine categories. The compared machine types are kinds of FSPM machine; with double stator structures. The magnets are mounted in the inner stators in such a way, that the closest magnets would always have opposite polarities to each other. The implemented models of the compared machine types are shown in Figure 1. Similarly, the basic machine parameters and employed materials are listed in Table 1.

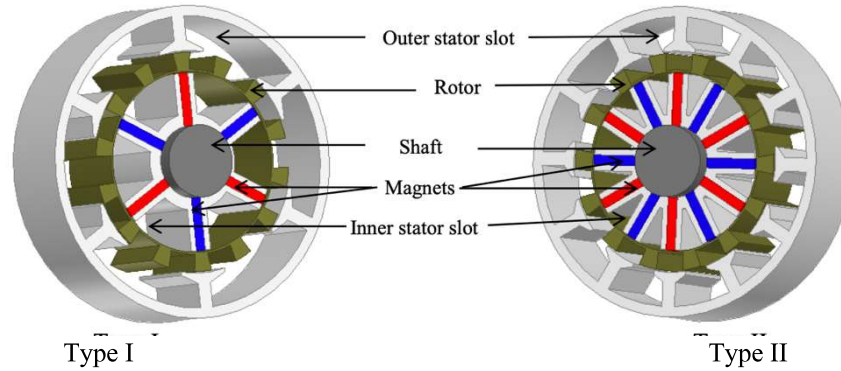


Figure 1: Compared machine models

Table 1: Basic machine parameters and values

Parameter	Value	
Machine Type	Type I	Type II
Inner stator slot number	6	12
Outer stator slot number	6	12
Number of coils per phase	2	4
Number of turns per coil	36	18
Spokes of magnet	6	12
Output power (P_o) at base speed	274.83 W	431.82 W
Maximum speed (n_m)	16000 rpm	8200 rpm
Base speed (n_b)	2800 rpm	2900 rpm
Direct-axis inductance	0.275 mH	0.167 mH
Constant power ratio (CPR)	5.71	2.83
Total number of turns/phase	72	
Rotor pole number	14	
Applied current	15 A	
Air-gap length	0.5 mm	
Stack length	25 mm	
Machine outer radius	45 mm	
Coil factor	0.6	
Core material	M330-35A	
Coil material	Copper	

Grade of magnet	N38SH
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The constant power ratio (CPR) of the analyzed machine is calculated as ratio of the maximum feasible speed (n_m) to its base speed (n_b), during field-weakening operation mode. The CPR expression is given in Eq. (1). This CPR ratio; Eq (1) is an indirect benchmark for measuring a machine's field-weakening capability (Hua *et al*, 2006). The predicted torque ripple (T_r) of the analyzed machine types is calculated using Eq. (2).

$$CPR = \frac{n_m}{n_b} \quad (1)$$

Estimated efficiency of the investigated machine types is mathematically expressed in Eq. (3), as implemented in Awah, (2022) and Jung *et al*, (2023).

$$T_r = \frac{T_{\max} - T_{\min}}{T_{\text{avg}}} \quad (2)$$

Where: T_{\max} , T_{\min} and T_{avg} is the maximum, minimum and average torque, respectively (Yu *et al*, 2023).

$$\eta = \frac{P_o}{P_o + P_i + P_{pm} + P_{cu}} \times 100\% \quad (3)$$

Where: P_o is the output power, P_i is the core or iron loss, P_{pm} is the eddy current loss due to the magnets and P_{cu} is the copper loss.

3. RESULTS AND DISCUSSION

The magnetic field vectors of the compared machines are presented in Figure 2. It is observed that the magnetic fields are more pronounced in Type II machine, and this feature would have positive impact towards the electromagnetic output of the machine, in terms of higher flux generation and consequent electromagnetic torque production. Also, the generated voltage of the compared machine types is shown in Figure 3(a) and (b). Again, Type II machine is seen to have higher voltage value than its Type I counterpart. The three-phase voltage waveforms of Type II machine seem to be more sinusoidal and symmetrical than that of Type I machine; the resulting fast Fourier transform (FFT) harmonic contents of the compared machines are provided in Figure 3(c). Meanwhile, the enormous non-fundamental harmonic elements of Type I machine would be detrimental to smooth operation of the machine, as highlighted in (Xu *et al*, 2010) and (Zhou and Zhu, 2014). Note that the generated voltage of Type I machine is only about 68.3% of its Type II equivalent.

Consequently, the generated electromagnetic torque value of Type I machine is much lower than that of Type II machine, as shown in Figure 4(a). The produced average torque of the machines as a function of applied copper loss is presented in Figure 4(b). It is worth noting that Type II machine has both larger electromagnetic torque and higher average torque than its compared Type I counterpart. The number of ripple in Type II machine is also doubled per electric cycle, since this feature would depend upon the machine's stator number and pole number arrangements, as inferred from Kwon *et al*, (2018).

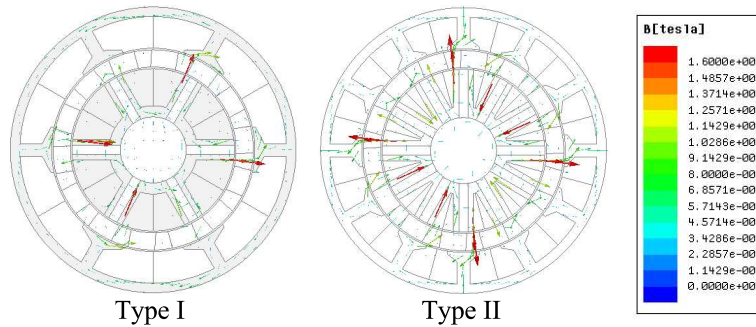
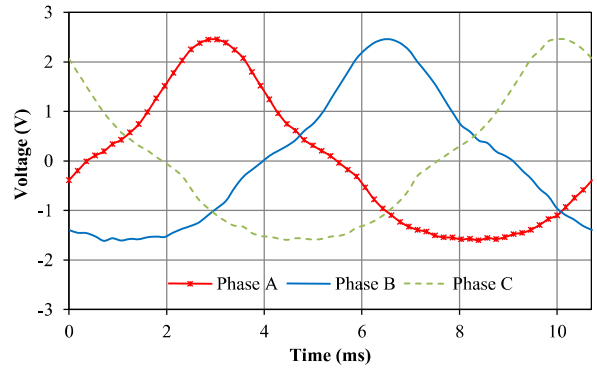
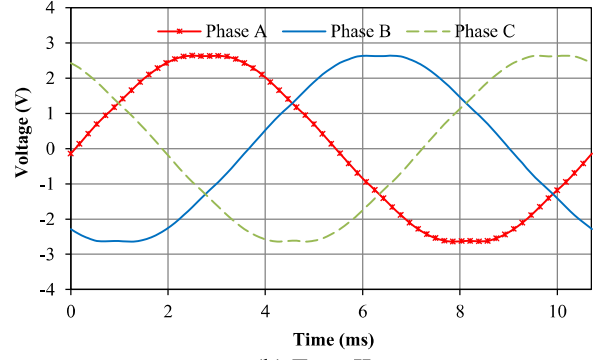


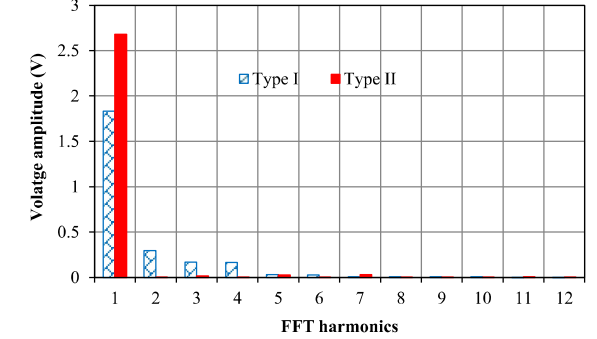
Figure 2: Magnetic vector contours, on open-circuit



(a) Type I



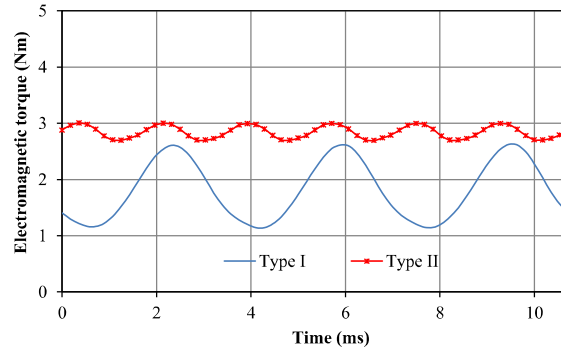
(b) Type II



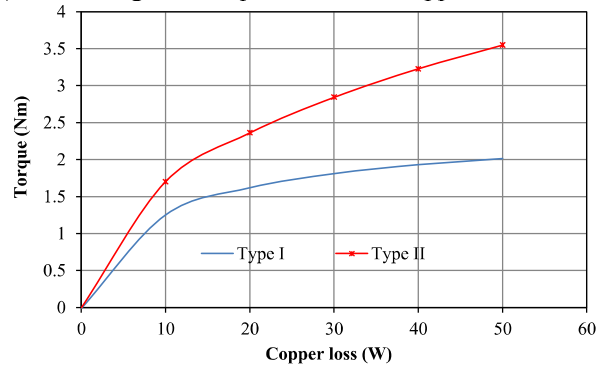
(c) Harmonic spectra

Figure 3: Comparison of induced voltage.

Furthermore, the torque-speed curves of the compared machine types are presented Figure 5. Obviously, Type I machine has wider speed coverage than Type II machine; albeit, with lower output torque value. It is worth mentioning that the speed of the compared machines would be largely dependent upon the machine’s direct-axis inductance, as well as on the flux linkage contribution owing to the magnets, as highlighted in Wang *et al*, (2023). Hence, Type I machine would naturally have better field-weakening ability than Type II machine, considering their respective maximum speed and base speed plus their predicted direct-axis inductance values, given in Table 1.



(a) Electromagnetic torque at constant copper loss condition



(b) Average torque

Figure 4: Torque comparisons.

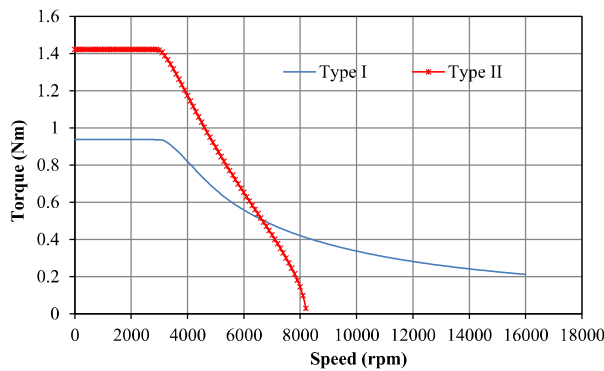
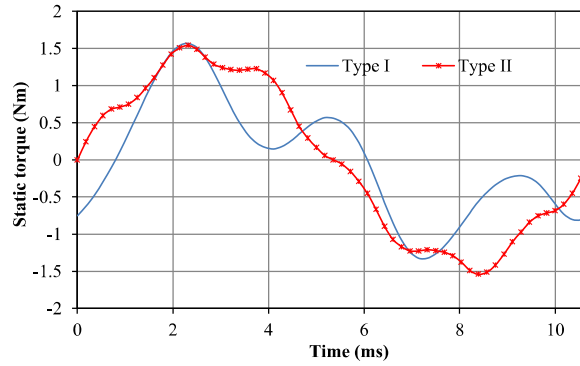
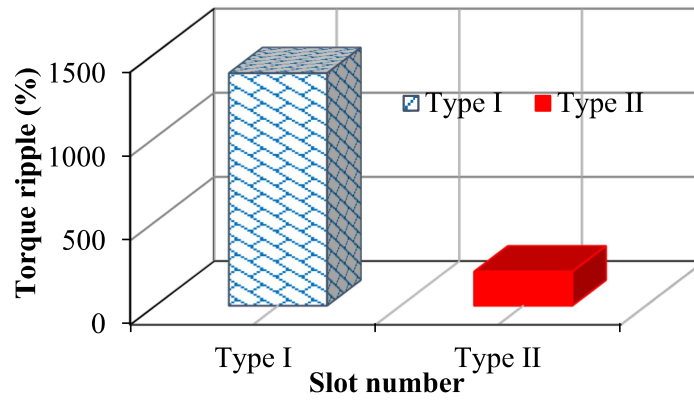


Figure 5: Torque-speed comparisons at rated current, 22.9 V

Figure 6 shows the static torque outlines and torque ripple values of the investigated machine types. Type II machine has a more uniform and symmetric waveform compared to that of Type I machine category. The uneven distribution of Type I static torque waveform could be attributed to its high unwanted harmonic contents; consequently, the resultant torque ripple value of Type I machine is noticeably higher than that of its corresponding Type II machine, as revealed in Figure 6(b). It is important to note that torque ripple amplitude of an electrical machine is a direct consequence of its harmonic contents, as highlighted in Owen *et al.*, (2010).



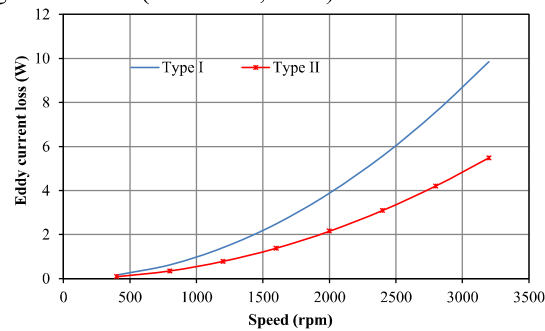
(a) Static torque



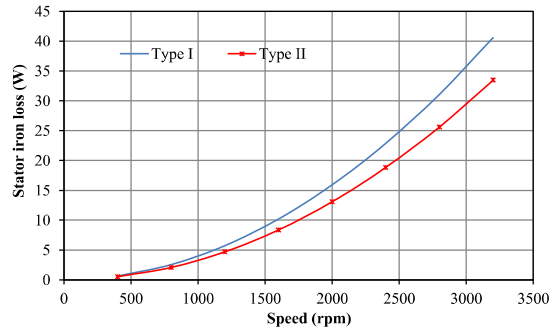
(b) Torque ripple

Figure 6: Static torque and torque ripple comparisons at 15 A.

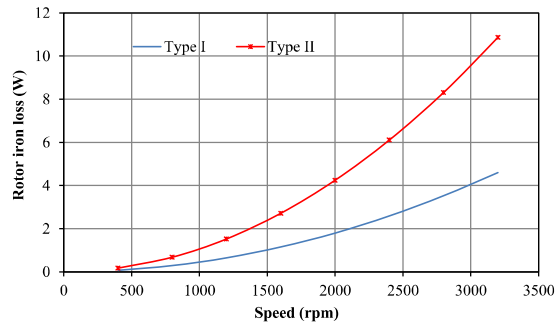
Although, Type I machine has higher eddy current loss and stator iron loss than the Type II machine, as shown in Figure 7(a) and (b); it has lower rotor iron loss than Type II machine, as shown in Figure 7(c). The predicted loss results are in conformity with the obtained loss results presented in Wang *et al*, (2014b). Meanwhile, Type I machine has better efficiency than Type II equivalent, at lower operating speed. Nevertheless, the Type II machine category exhibits superior efficiency potential at high working speed, compared to Type I machine; as depicted in Figure 8. Moreover, enhanced machine efficiency could be realized from an electric machine by implementing newly developed soft magnetic core materials, which certainly reduces a machine's overall loss value or through appropriate segmentation of the applied magnet material (Chen *et al*, 2020).



(a)



(b)



(c)

Figure 7: Loss comparisons.

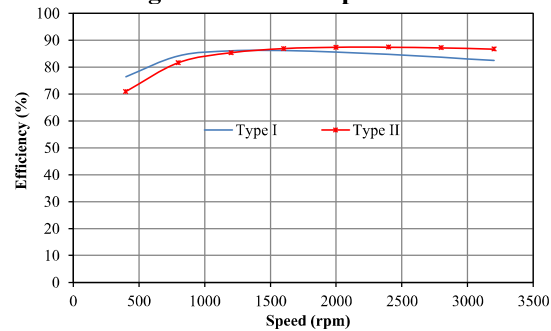


Figure 8: Comparison of efficiency.

4. CONCLUSION

Influence of stator slot number on the performance of a given double stator permanent magnet machine is analyzed and compared in this study. The increased number of slots in this investigation yielded higher induced-voltage value, larger output torque, lower undesirable harmonic contents, lower torque ripple value and evenly-distributed voltage and static torque waveforms, amongst other merits. Type I machine exhibits higher potential for high speed machine applications, as well as better efficiency at low working speed compared to Type II machine category. The investigated machine types would be suitable in low speed high torque direct-drive applications. About 34.5 % and 31.7 % increase is realized in the torque and induced-voltage magnitudes of the investigated machine, by doubling the slot number from six (6) to twelve (12), under normal working conditions. The obtained output power of the machine increased from 283.81W to 431.82 W, as a result of the slot number increase.

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