

# Electromagnetic performance of a two-stator permanent magnet machine

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**Abstract**-The electromagnetic performance of permanent magnet (PM) machine having set of two different stators is presented in this paper. The investigated machine elements are: air-gap flux density, magnetic coercive force, flux-linkage, output torque, torque ripple, total harmonic distortion (THD), losses and efficiency. Two-dimensional finite element analysis using MAXWELL-software is implemented in the whole predictions. The machine optimal dimensions are obtained from the inherent genetic algorithm optimization technique of the employed software. The proposed machine has one ring type of cup-shaped rotor which is sandwiched between the inner stator and outer stator. The studies show that the proposed machine has better electromagnetic torque than its one-stator counterpart. More so, it has lower total loss and improved efficiency than the single-stator equivalent. The investigated machine is suited for high torque low speed machine operations, such as in in-wheel direct drives; hence, it could be employed in automobile and traction applications.

**Keywords:** *Efficiency, rotor loss, stator loss, torque, and two-stator.*

## 1. Introduction

Low speed high torque machines are gaining a lot of interest due to its good suitability for direct-drive applications. Hence, a permanent magnet machine having two-stator architecture is designed and presented in this current study, in order to offer high torque at low operating speed. However, research by Zou *et al* (2017) has shown that high torque machines may incidentally necessitate large machine overall volume or size. More so, reports in Liu *et al* (2012) and Zou *et al* (2017) show that permanent magnet machines with either dual stator and or dual air-gap features are capable of delivering higher output torque compared to the ones with single stator and or single air-gap, respectively. Similarly, a detailed study offered in Li *et al* (2016) show that by doubling the stator segment of flux-switching PM machine, a reasonable reduction in cogging torque and total harmonic distortion could be achieved, added to an impressive high output torque and efficiency; though, with increased machine size and relatively higher cost when compared with the single stator counterpart.

In addition, the ability of any given electrical machine to produce high torque at low speed would also depend mainly on its potential to modulate enough flux harmonics around the air-gap coupled with the implementation of high rotor pole numbers in the machine (Chung *et al*, 2012). Conversely, for high-speed operation, low number of rotor poles is required. Moreover, flux-focusing technique also enhances the output torque of electric machines due to the nature of its operational flux density. It is worth pointing out that the proposed machine in this present study not only has dual stator and dual air-gap structural design, but also has high capability for flux-focusing skill owing to its spoke-arranged magnets. More so, the proposed machine in this present study also belongs to the family of magnetically-geared PM machines.

A high-performance PM machine having permanent magnets on both the stator and rotor is proposed in Jian *et al*, (2013) for effective operation in low speed direct-drive applications. Nevertheless, the proposed machine in Jian *et al*, (2013) consumes a lot of PM materials, in addition to its in-built complicated structural arrangement and this will possibly hamper its viable fabrication, due to the associated high cost implications.

Magnetically-g geared PM machines which integrate the potentials of conventional PM machines and that of magnetic gears has a lot of merits such as high torque density, little maintenance, lower noise and vibration over traditional PM machines (Morimoto *et al*, 2014) and (Gerber and Wang 2015). It is worth noting that magnetically geared PM machines are promising candidates for low speed high torque direct-drive operation. Moreover, both the output torque and power factor of PM machines could be improved by employing the Halbach magnet technology, where high flux-concentration is realized from the scattered PM arrangement, as detailed in Xu *et al*, (2016). Nevertheless, the geared-PM machines are usually disadvantaged in terms of poorer power factor as reported in Zhang *et al*, (2015) combined with high manufacturing cost, relative to the conventional PM machines.

The proposed machine diagram is depicted in Figure 1. More so, the proposed machine parameters and values are listed in Table 1. Basically, a new type of two-stator permanent magnet machine is developed and recommended in this paper for high torque electrical machine operations.

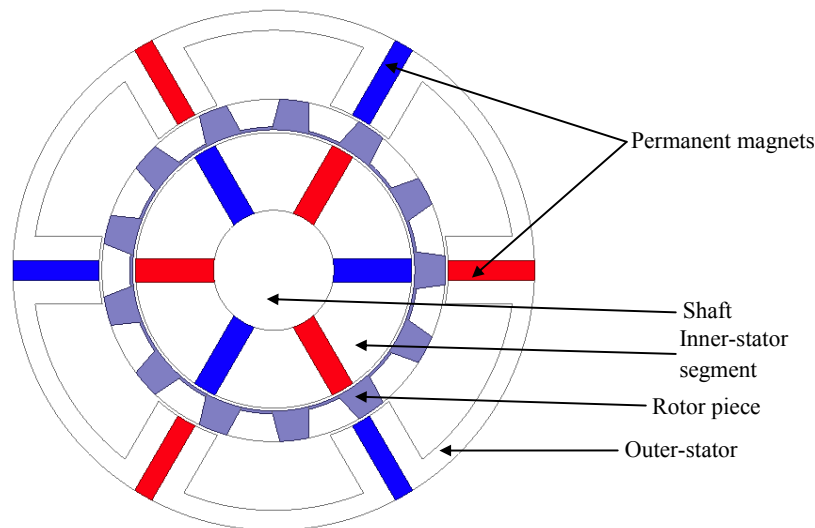


Figure 1. The proposed new machine structure.

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Item	Value
No. of stator slots	6
No. of rotor poles	13
Air-gap size (mm)	0.5
Axial length (mm)	25
Machine outer radius (mm)	45
Copper loss (W)	30
Split ratio	0.66
Packing factor	0.6

Load torque (Nm) at fixed copper loss	4.66
Outer-stator back-iron size (mm)	3.4
No. of turns / phase	72
Torque ripple at 10A (%)	15.83
Open-circuit torque (Nm)	0.1221
Total harmonic distortion (%) at 10A	9.29
Sum of iron loss and magnet loss (W) at fixed copper loss, 400rpm	1.54

The injected 3-phase alternating current is given in equation (1).

$$\begin{aligned}
 I_R &= I_m \sin(\omega t) \\
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 \end{aligned} \tag{1}$$

Where,  $I_m$  is the maximum value of current,  $\omega$  is the angular speed and  $t$  is the electric period.

The variation of air-gap flux-density with its matching coercive force is shown in Figure 2. The respective peak values of the above mentioned variables are 2.01 Tesla and 1600.69kA/m. It is observed that both the air-gap flux-density and the coercive force are not quite uniform across the whole rotor positions, likely due to inherent harmonics in the air-gap region.

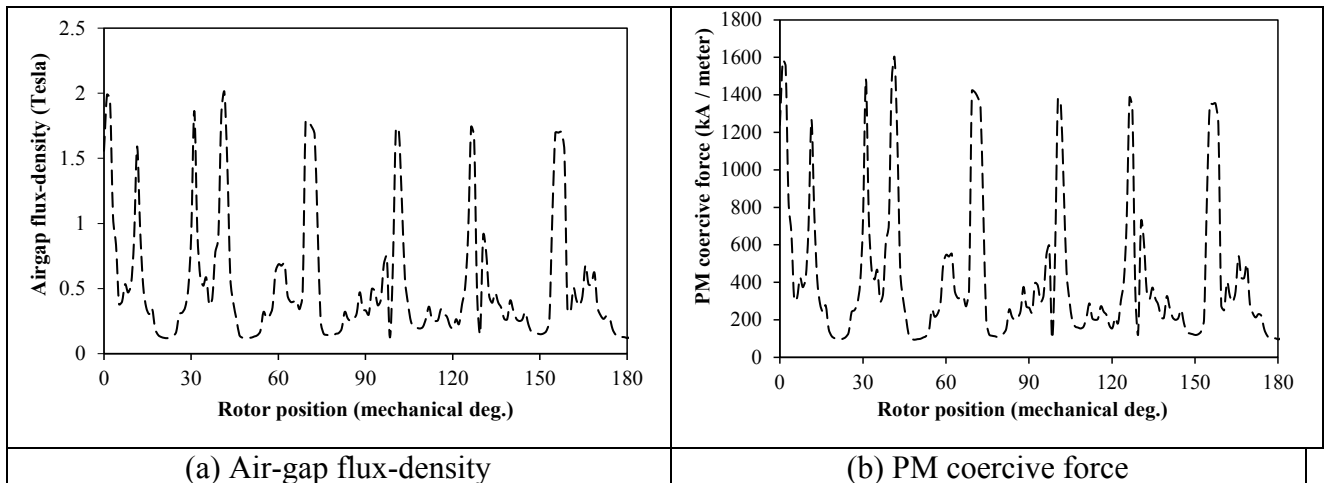


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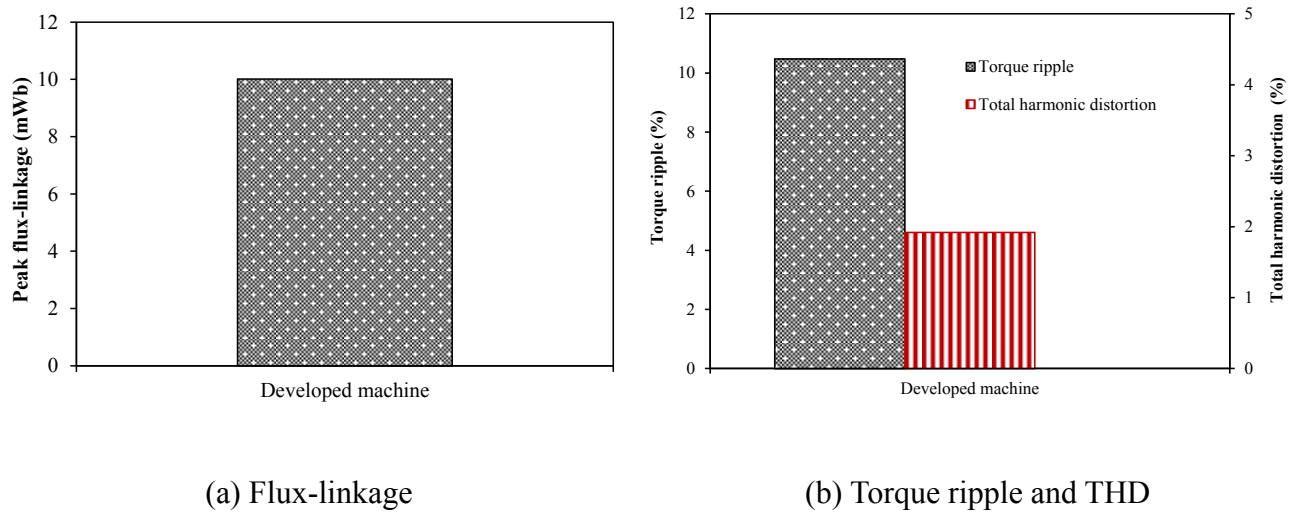


Figure 3. Comparison of flux-linkage, torque ripple and total harmonic distortion.

The torque ripple factor of the investigated machine is roughly 10%, which is also practically acceptable.

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The comparison of output torque across the rotor positions is shown in Figure 4. It is clear that the proposed machine has about 30% larger torque than its single stator equivalent with trivial amount of 6<sup>th</sup> order harmonic, as shown in Figure 4(b). Further, the compared machines have comparable output torque per PM volume at low load conditions as shown in Figure 5. However, the proposed machine would have a competitive advantage at high current-density load.

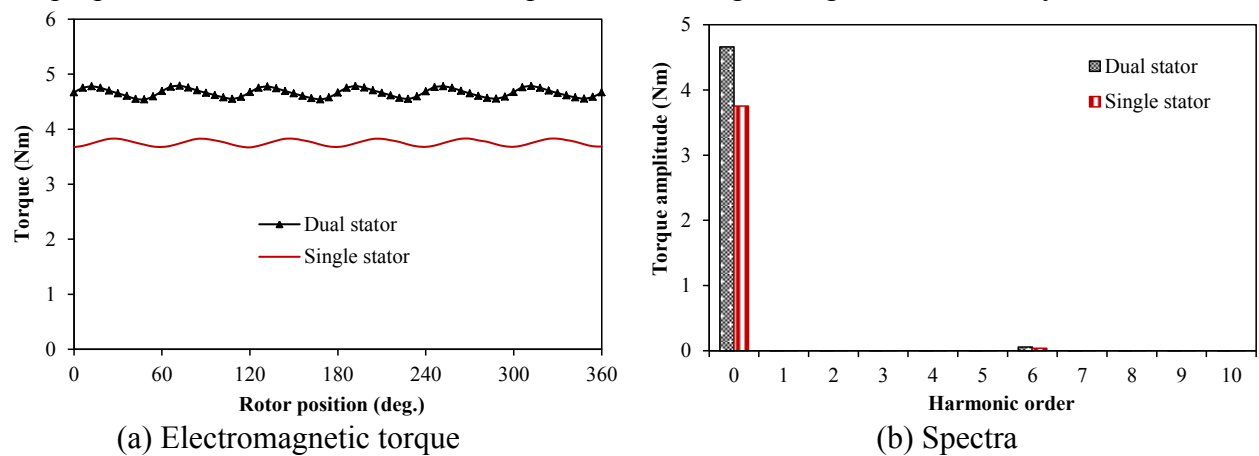


Figure 4. Comparison of electromagnetic torque at constant copper loss.

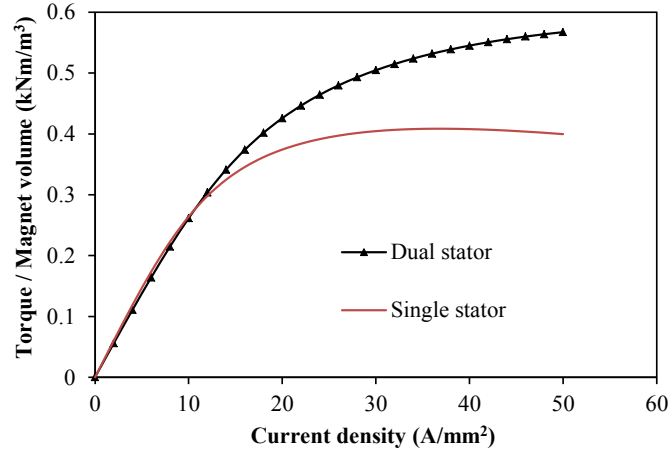


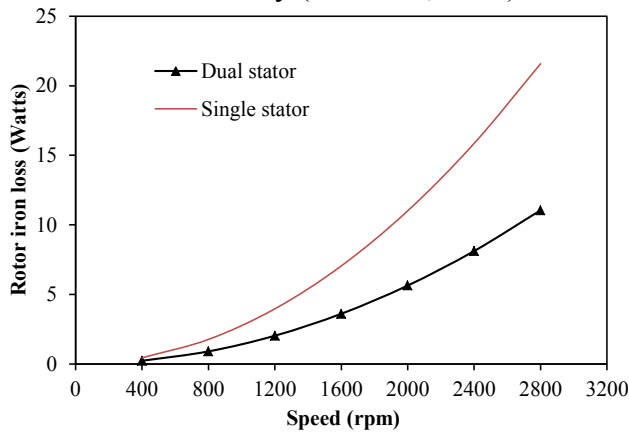
Figure 5. Comparison of torque per magnet volume.

The rotor and stator core losses of the investigated machines are given in Figure 6. The predicted results show that the proposed machine has lower rotor iron loss and slightly higher stator iron loss; though with an overall lower loss content when compared with its single stator counterpart, as depicted in Figure 7. It is worth noting that the predicted total losses in this study are: stator and rotor iron losses, copper loss, and eddy current loss contribution from the PMs. However, experienced has shown that the use of soft magnetic core materials can help to reduce the core loss of a given electric machine, as noted in Prabhu *et al*, (2016). Also, it is proved in Thomas *et al*, (2012) that by adopting a modular-rotor structure, then, both the PM eddy current loss and iron loss of a PM machine could be considerably reduced. However, machines with modular structures could adversely increase the eccentricity level of such machines, as stated in (Hua *et al*, 2015) and would even worsen the vibration inadequacy (Valavi *et al*, 2015) of the machine. Moreover, the compared results reveal that the proposed machine has an improved efficiency in relation to its single stator equivalent.

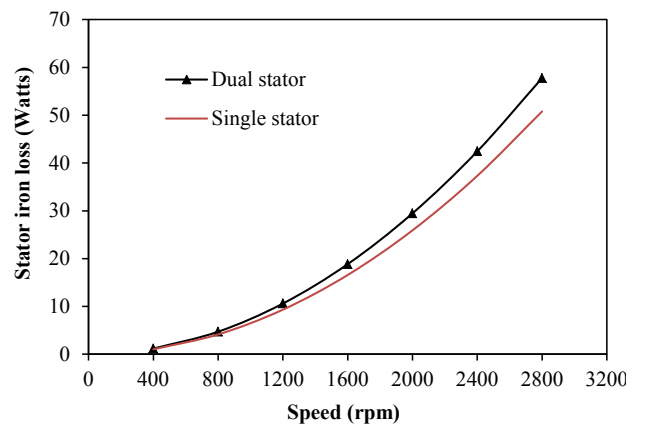
Furthermore, the estimated machine losses are predicted using equation (2).

$$Iron\ loss = k_{hst} B^2 f + \frac{\pi^2 k_{th}^2}{6\rho} B^2 f^2 + k_{excess} B^{3/2} f^{3/2} \quad (2)$$

Where,  $k_{hst}$  is the hysteresis coefficient,  $k_{th}$  is the thickness of the core laminations,  $k_{excess}$  is the coefficient of excess loss,  $\rho$  is the resistivity of the material,  $f$  is the frequency and  $B$  is the maximum flux density (Gao *et al*, 2018).



(a) Rotor iron loss versus speed



(b) Stator iron loss versus speed

Figure 6. Comparison of rotor and stator iron losses.

Similarly, the overall efficiency of any given electrical machine is quoted in equation (3), as stated in (Gao *et al*, 2018). However, note that windage and frictional losses are neglected in this present calculation.

$$\eta = \frac{\text{Output power}}{\text{Output power} + \text{Total losses}} \quad (3)$$

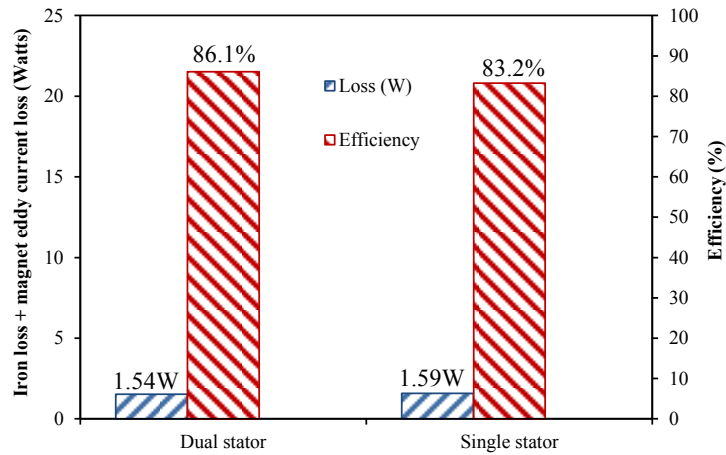


Figure 7. Comparison of loss and efficiency at constant copper loss, 400 rpm.

### 3. Conclusion

A new type of permanent magnet machine having duo stator is presented. The proposed machine is capable of delivering higher electromagnetic torque and better efficiency than its single stator equivalent. Nevertheless, the proposed machine has comparable output torque per used PM volume, with its single stator equivalent, at low electric conditions. However, the machine performance in relation to PM usage of proposed machine outweighs that of the single stator PM machine at high electric loadings. The proposed machine could be employed in power generation, automobile and traction applications.

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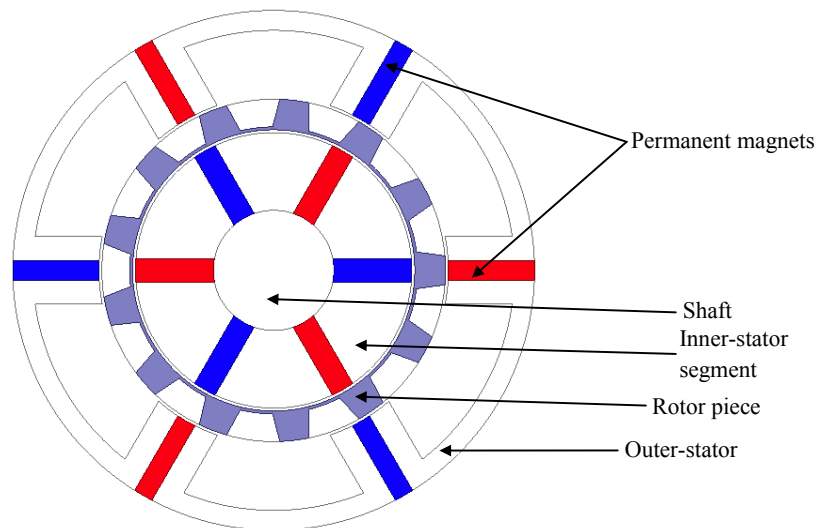


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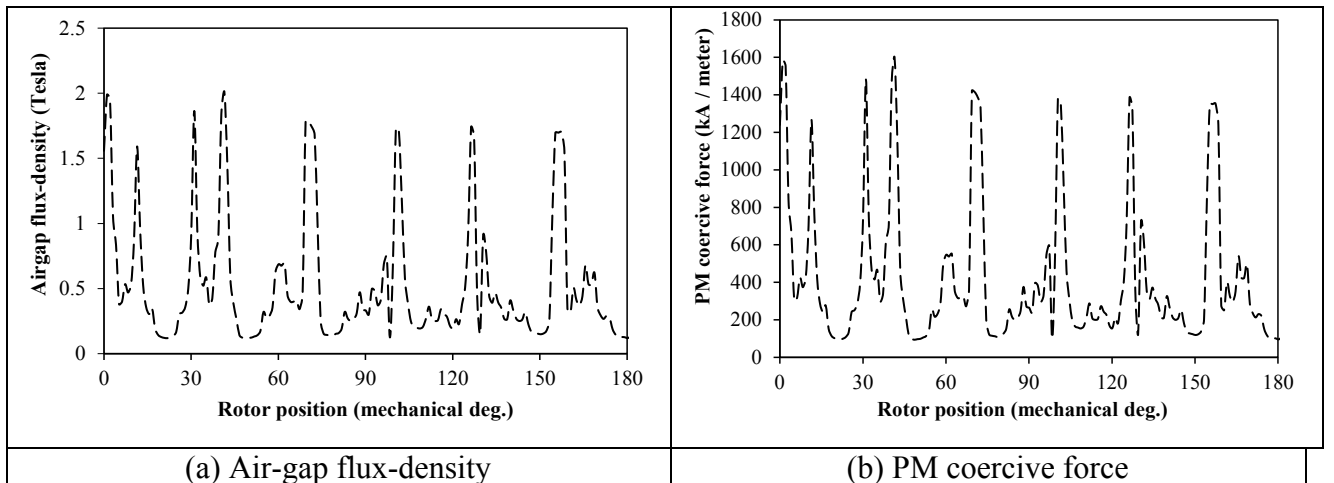


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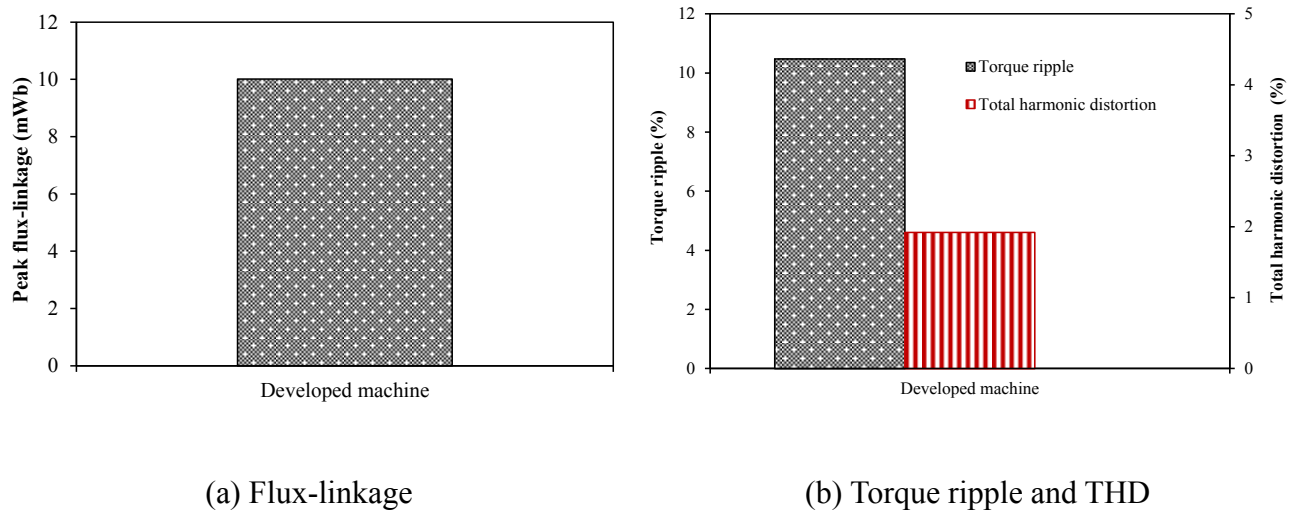


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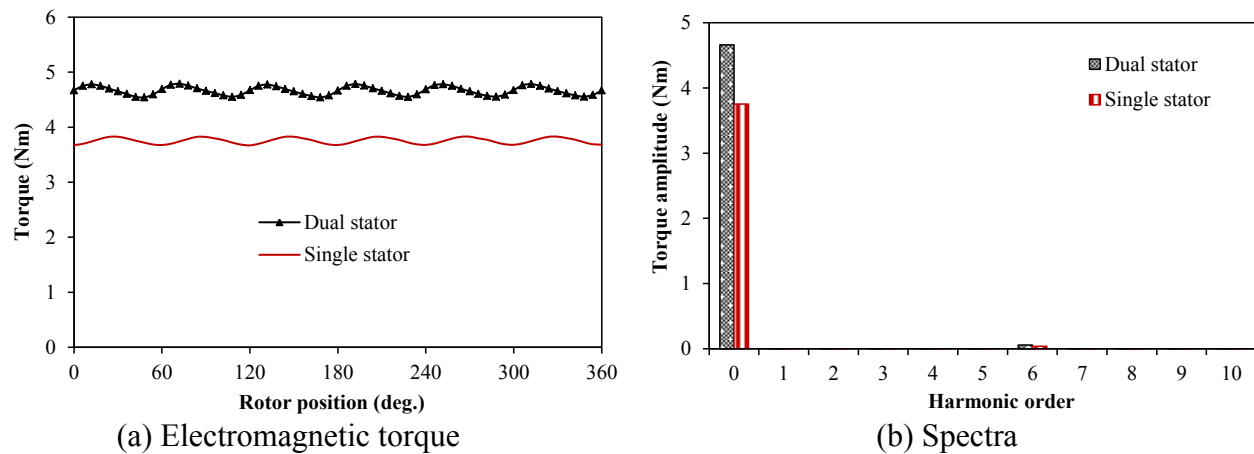


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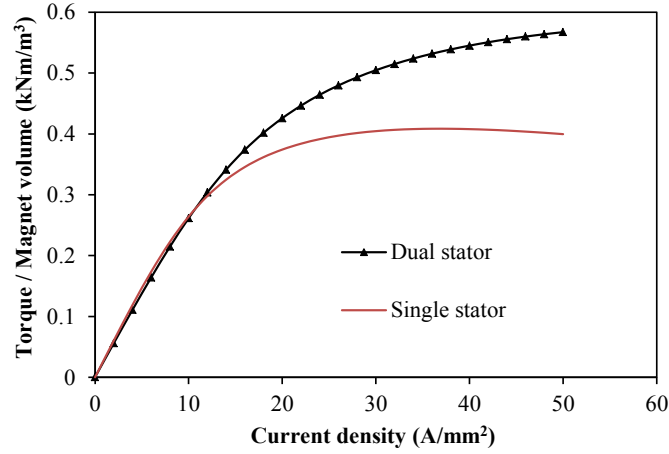


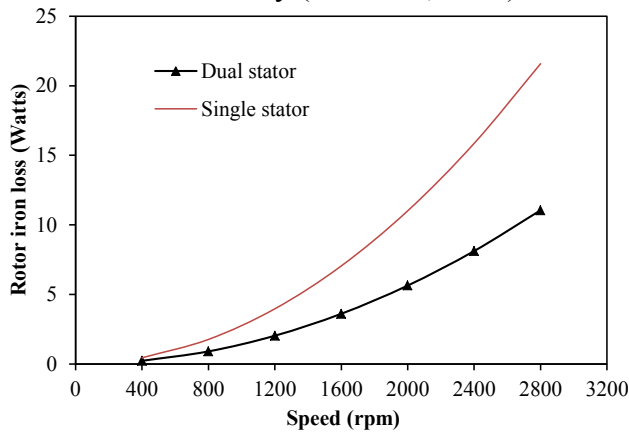
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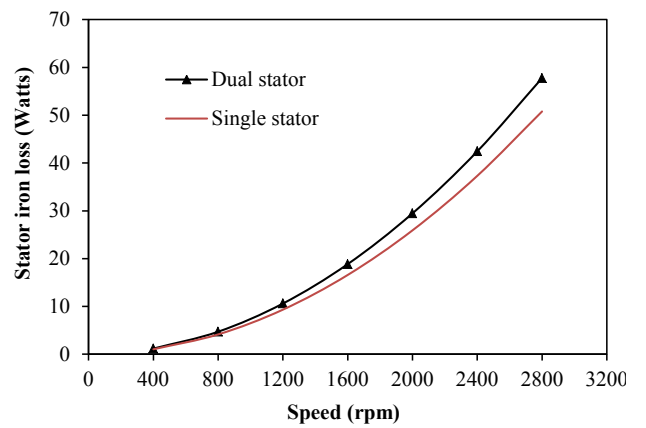
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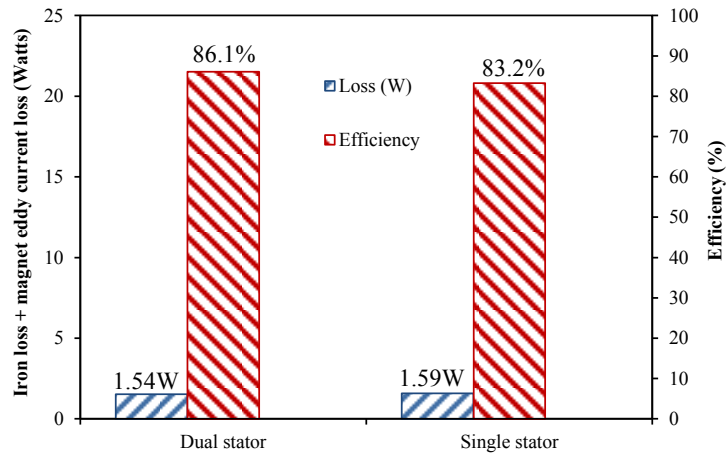


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