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ELECTROMAGNETIC AND ELECTROMECHANICAL PERFORMANCE EVALUATION OF DUAL STATOR FSPM MACHINE WITH VARYING STATOR TEETH THICKNESS

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Abstract

Electromagnetic and electromechanical significances of stator teeth thickness on electric machine outputs are presented in this study. The studied machine is a dual-stator (DS) flux-switching permanent magnet (FSPM) machine. Maxwell-2D finite element analysis is implemented. The investigated machine metrics include: flux linkage, induced-voltage, power, inductance, torque and magnetic force. The compared machine types having equal and unequal stator teeth thickness have its merits and demerits. Generated largest voltage and torque of the equal stator-toothed machine type at rated conditions is 4.75 V and 2.48 Nm, respectively. The developed machine type having unequal stator tooth thickness has matching voltage and torque value of 4.84 V and 2.54 Nm, respectively. Nevertheless, the developed machine type has lower flux-weakening capability, owing to its slightly lower speed range compared to the equivalent machine that has equal stator tooth structure.

1.0 INTRODUCTION

Stator tooth thickness and its associated influence on the performance of an electric machine cannot be underrated or unappreciated, as inferred from [1]. Single stator E-core machine having different tooth sizes was proposed in [2]; the proposed single stator E-core machine has its pole number numerically equal to half of its stator teeth number. The studied E-core machine is revealed to have higher torque density and better electromagnetic outputs compared to its equivalent conventional flux-switching machine. Similarly, a dual stator electric machine having E-core stator tooth structure was proposed in [3]; however, it has equal stator teeth structure. Thus, the influence of stator tooth thickness of the investigated machine in this present study is considered necessary at this time, as a guide to electric machine designers about the significance of stator teeth size (s) on electromagnetic and electromechanical performances of the machine. Similarly, the stator teeth and rotor pole numbers of an electric machine would have great influence in most of its electromechanical and electromagnetic outputs, as demonstrated in [4].

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The resulting torque of a flux-switching permanent magnet (FSPM) machine would be dependent upon its stator tooth thickness and its consequence conductor area; in addition to the slot opening sizes [5]. An equal ratio between stator tooth thickness and the matching slot opening size is recommended in [5], for optimal torque generation.

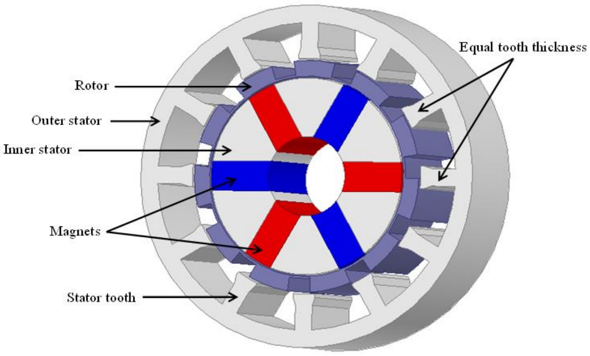
Additionally, magnitudes of torque and speed of a given electric machine could be varied and regulated using different control strategies, such as: proportional-integral (PI) and proportional-derivative (PD) controller techniques [6]. Although, proportional derivative controller approach is recommended in [6] over its proportional-integral method; however, both techniques have its distinct merits and demerits. It is important to note that these control techniques also involve the manipulation of voltage and frequency values of the given electric machine, in order to achieve optimal machine efficiency.

It is revealed in [7] that implementation of unequal stator tooth thickness of a machine coupled with suitable optimization of its key structural variables would result to reduced torque ripple, lower voltage distortion as well as more symmetrical and sinusoidal voltage waveforms, etc., besides its increased fault-tolerance attribute. Most of these features are vital in electric motor control and drive operations. Efficacy of unequal stator tooth thickness in reducing the machine's torque ripple index is ascertained in [8] and by extension, unwanted harmonic contents of the machine could be drastically reduced through this unequal stator tooth implementation scheme [9].

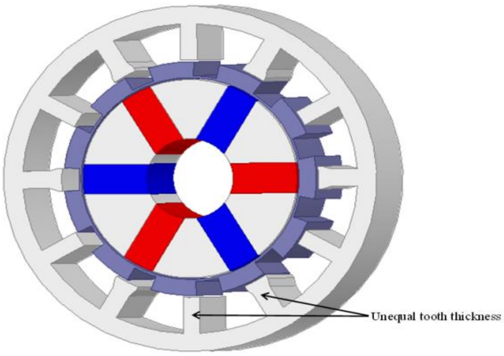
Asymmetric stator teeth could yield competitive output characteristics in a machine, as demonstrated in [10]. More so, the reliability and fault-tolerance potentials of a machine that has unequal stator tooth thickness is emphasized in [11], in addition to such a machine's economical competiveness. This is achieved by its magnetic isolation and decoupling abilities between the relevant phases and coils. The utilization of unequal stator tooth thickness of a machine in enhancing its fault-tolerance capability is proved in [12].

An electric machine that has asymmetric stator teeth plan is proved to have higher flux adjustment and extended speed range possibilities [13], compared to its counterparts with symmetric stator tooth arrangement. Nevertheless, the implementation of asymmetric stator teeth structure is associated with higher cost and lower power factor implications. Asymmetric stator tooth arrangement can improve the magnetic saturation withstand sustainability plus overall machine output performance [14]; however, special consideration must be made for rotational direction of the rotor, in order to maximize this technique. Similarly, significant reduction in cogging and reluctance torque could also be realized from a machine by adopting asymmetric stator teeth structure [15]; albeit, with negligible reduction in its useful torque value. By extension, the use of unequal stator tooth thickness in mitigating cogging torque and other undesirable machine characteristics could be applied with its magnetic poles [16]; although, it would attract slight level of mechanical instability on the machine, as a penalty.

A three-phase dual stator machine having two (2) different stator teeth thickness is analyzed and compared in this study using finite element analysis approach. The study is intended to provide concise package on the effects of stator tooth thickness on both electromagnetic and electromechanical performances of the machine. The relevant sections of this investigation are: Introduction, methodology, results and discussion and conclusion.



1(a): Existing structure having equal stator tooth thickness [3]



1(b): Developed structure having unequal stator tooth thickness

Figure 1: The investigated structures

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2.0 METHODOLOGY

Finite element analysis is applied in the entire computation. The studied machine structures having both equal and unequal stator tooth thickness are displayed in Figure 1. Total magnetic flux in an FSPM machine is jointly contributed by both the magnets and armature windings; however, the resulting flux is largely dominated by components due to magnets. An insignificant portion of the total flux is obtained from the armature windings. Owing to this large flux contribution by the magnets, about 99 % of generated shaft torque is usually gained from the magnetic component. This high percentage contribution is a unique property of FSPM machine, because it is characterized by trivial reluctance torque worth [17]; unlike some other electrical machines that have more torque production from the machines' reluctance torque, due its large saliency impacts.

The maximum flux component due to magnets (ϕ_{mag}) is expressed in Equation (1), as detailed in [18]. Note that FSPM machine's phase flux linkage and voltage waveforms are typically bipolar, having similar positive and negative maxima values. The machine's induced-voltage (E) is given in Equation (2). Also, its output power (P_o) is expressed in Equation (3).

It is worth noting that the investigated machine is an FSPM machine, however of dual stator structure. Generally, dual stator machines are more expensive and usually have more complex structure than its equivalent single stator counterparts; though, with remarkable electromagnetic outputs. The fundamental machine parameters and its values are enumerated in Table 1. The investigated machine's operating principle is based upon both flux-switching and magnetically-gearing principles, as detailed in [19].

$$\phi_{mag} = \left|\phi_p \cos\left(P\theta\right)\right| \tag{1}$$

Where; ϕ_p is peak flux within a pole pitch period, P is pole number and Θ is electrical rotor positions [18].

$$E = -N\frac{\Delta\phi}{\Delta t} \tag{2}$$

Where; N represents winding turns number, Δ is change symbol; ϕ is flux linkage, t is simulation time [20].

$$P_o = \omega T \tag{3}$$

Where; ω is the rotational speed and T is output torque [21].

Table 1: Basic machine values

Machine structure	**Existing machine**	**Developed machine**
Stator tooth thickness, mm	4.55	4.55 and 4.00
Slot area, mm^2	$130253 \text{ x}10^{-6}$	$134203 \text{ x}10^{-6}$
Phase resistance, Ω	0.0557	0.0541
Maximum speed, rpm	4500	4300
Knee speed, rpm	1800	1700
Stator teeth number	6	
Poles	11	
Stator diameter, mm	90	
Rated current, A	15	
Turns number	72	
Magnet	Neodymium	
Core material	M330-35A	
Coil material	Copper	

3.0 RESULTS AND DISCUSSION

Magnetic flux contours of the compared machine types are presented in Figure 2. The investigated machine types have fairly similar magnetic flux outlines. Open-circuit flux linkage outlines and the corresponding harmonic amplitudes of the compared machine types are shown in Figure 3(a) and (b). The machine type that has unequal stator tooth thickness displays quite higher flux linkage amplitude than its existing counterpart having equal stator-toothed structure. Consequently, resulting induced-electromotive force (EMF) is higher in the developed machine type by about 1.43 %, as depicted in Figure 3(c).

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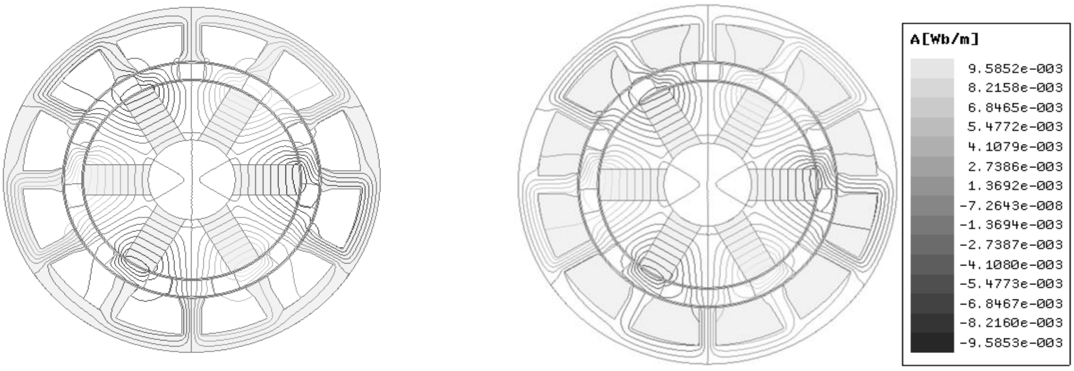
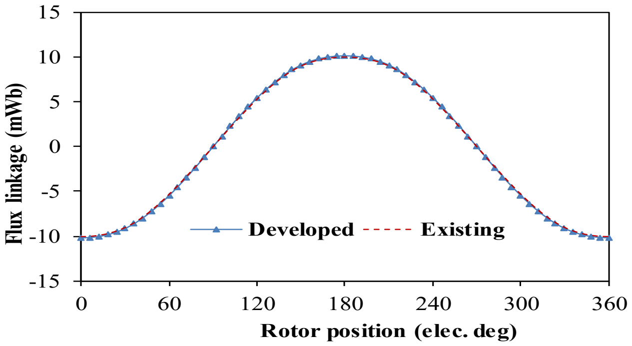
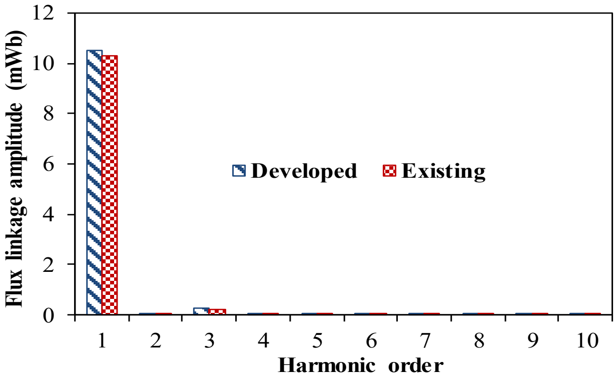


2(a): Existing **2(b):** Developed

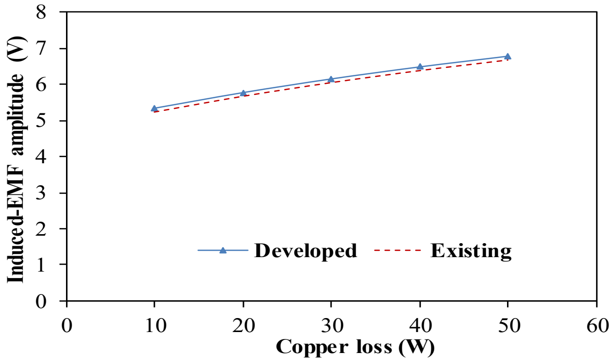
Figure 2: Magnetic flux lines



3(a): Flux linkage



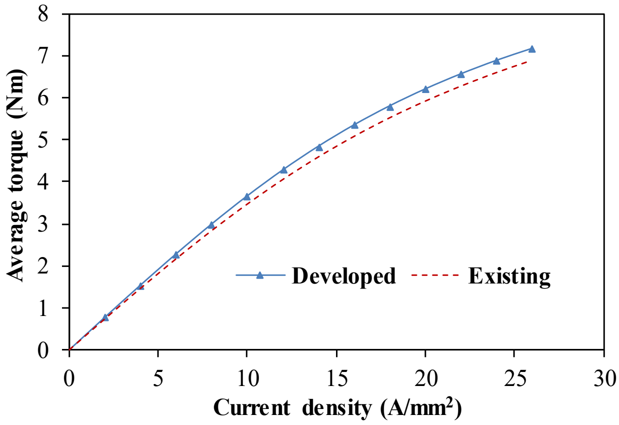
3(b): Harmonic amplitude



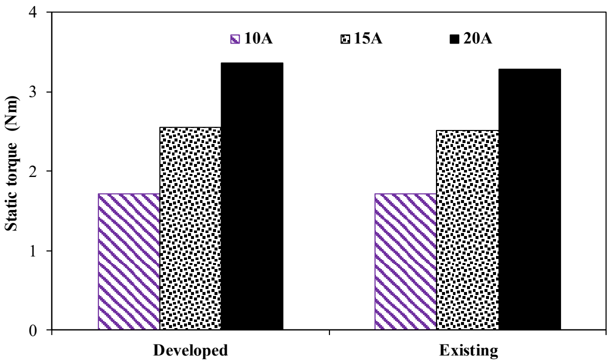
3(c): Electromotive force versus copper loss

Figure 3: Comparison of phase flux linkage and induced-EMF comparisons

The FEA predicted average and static torques are presented in Figure 4(a) and (b). Again, the developed machine has larger average torque of approximately 3.00 Nm at 8 A/mm^2 compared to 2.84 Nm of the existing machine type. More so, the developed machine category has greater static torque value of about 2.56 Nm compared to its equivalent 2.51 Nm of the existing machine, at rated current. This higher torque value advantage of the developed machine type is maintained at all simulation conditions. Linear relationship exists between the supplied loads and the resulting torques, as shown in Figure 4(a) and (b). Meanwhile, magnetic flux, induced-voltage and torque of electric machines are directly related to each other, as highlighted in [22].



4(a): Average torque



4(b): Static torque

Figure 4: Comparison of average and static torque

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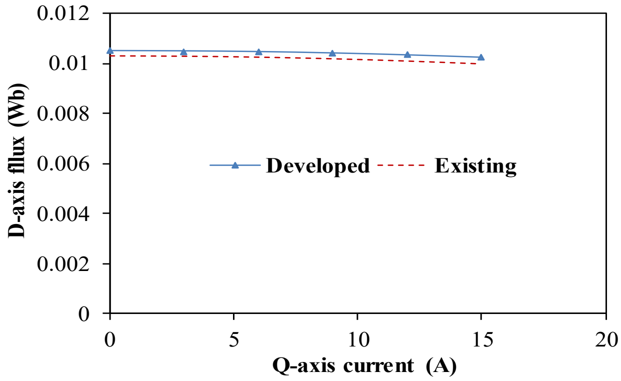
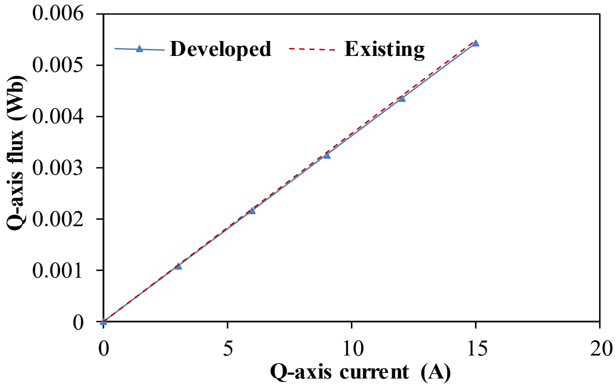


5(a): Direct-axis flux versus current

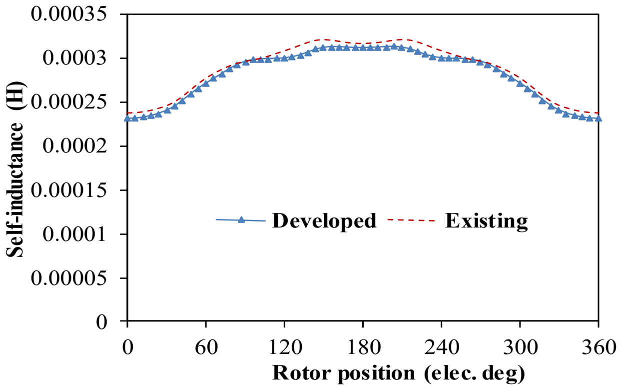


5(b): Quadrature-axis flux versus current

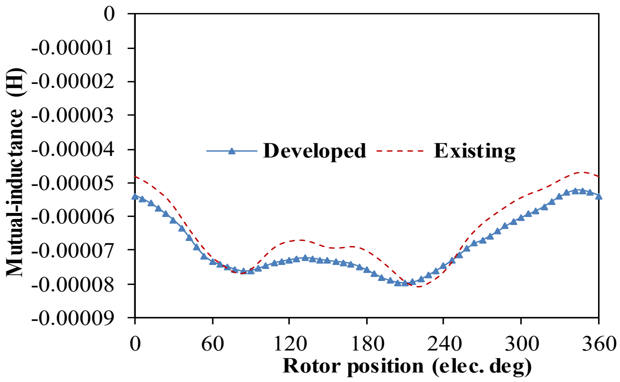
Figure 5: Comparison of axes flux

Axes flux of the studied machine types are presented in Figure 5, computed over different quadrature (*Q*)-axis current ratings. It is revealed that the developed machine has practically similar quadrature-axis flux and larger amount of direct (*D*)-axis flux compared to the exiting machine topology. The direct-axis flux amplitude seems to decease with increasing current, due to the effect of armature reaction.

Predicted average values of self-inductance in the machine types having equal and unequal tooth thickness is approximately equal to 0.29 mH and 0.28 mH, respectively. The compared machine models have matching mutual inductance value of -0.065 mH and -0.068 mH, correspondingly. The predicted inductance outlines are shown in Figure 6. A machine that possesses high value of self-inductance and low mutual inductance value is needed for fault-tolerance sustainability activities [23]. It can be concluded that the investigated machine types have advantages of high self-inductance obtainable from equal stator-toothed machine topology and low mutual inductance from the unequal stator-toothed machine configuration. Therefore, each of the compared machine types has its individual peculiarities, in terms of merits and demerits, as could be deduced from Figure 6(a) and (b), separately. The axes inductance is higher in the existing machine type by 1.65 % compared to the developed one, at rated load. However, it is worth mentioning that high amount of axes inductance in a machine can affect its saturation level negatively and would subsequently reduce its electric overloading potential, as highlighted in [24] and [25]. Furthermore, the magnetic force amplitudes on the rotor of the analyzed machine types are compared in Figure 8; though, these machine types have dissimilar magnetic force waveforms or outlines. It is also glaring that the resulting rotor magnetic force is directly proportional to the applied load current; the relative difference in force magnitude increases at higher electric loadings.

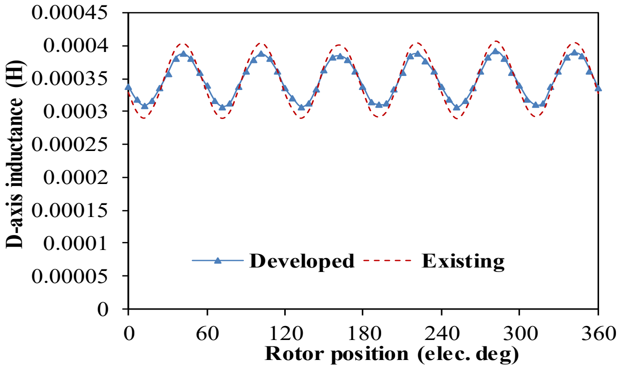


6(a): Self inductance



6(b): Mutual inductance

Figure 6: Comparison of self and mutual inductances



7(a): Direct-axis inductance

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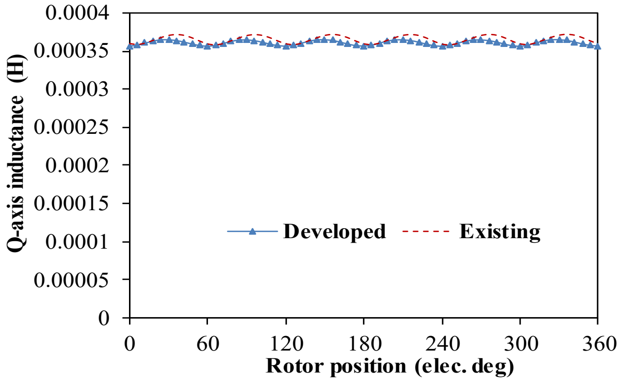
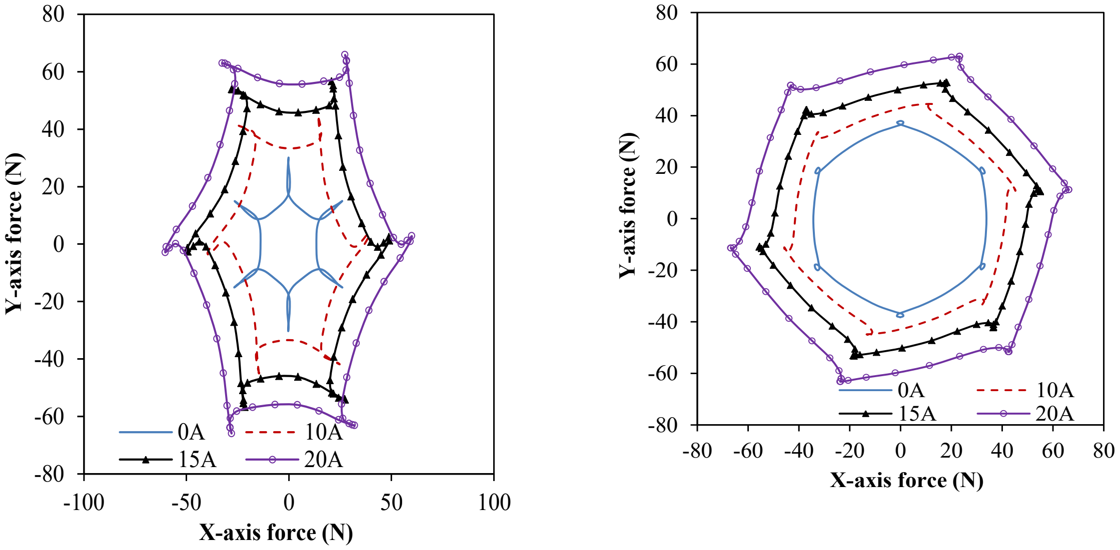


7(b): Quadrature-axis inductance

Figure 7: Comparison of axes inductance

The existing machine has longer speed range than the developed machine, as shown in Figure 9. Although, longer speed range is a desirable machine quality; however, mechanical stress on a machine is directly related to its speed rating [26], an enlarged speed rating would usually result to more mechanical stress on the device. Thus, the existing machine would battle with marginally higher amount of mechanical instability relative to its equivalent developed machine type. It is worth noting that the developed machine has slightly higher power value of 106.30 W than the existing machine which has a corresponding power of 103.78 W, at rated load and speed conditions; however, the resulting shaft power of existing machine outweighs that of the developed machine at high operating speed. The axes inductance values of a machine and hence, its matching saliency ratios (i.e. the axes inductance ratios) [27] is vital in determining its power and torque ratings [28] as well as the consequent speed coverage; particularly, under field- or flux-weakening situation [29]. Meanwhile, these machine's metric parameters may also be influenced by the machine's inductance non-linear effect, especially at constant power operating region [30].



8(a): Existing

8(b): Developed

Figure 8: Comparison of unbalanced magnetic force

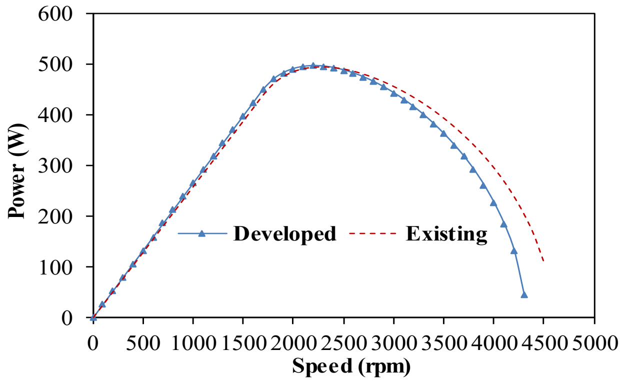


Figure 9: Power versus speed

4.0 CONCLUSION

Performance comparison of a machine that has two (2) different stator tooth thickness is studied and presented in this current research using finite element technique. It is shown that the machine type that has unequal tooth thickness exhibits larger percentage flux and voltage value of 1.87 % each, at open circuit condition. It also displays greater percentage torque and power value of 2.37 % and 2.35 %, respectively, at rated load conditions; in addition, with lower inductance value. Predicted shaft power of the machine type having equal stator tooth thickness is higher at high speed operation; which is a good flux-

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weakening feature for traction and vehicle uses. The compared machine types have comparable magnetic force on its rotor. Each of the investigated machine types possesses distinct advantages and disadvantages, depending on application context.

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