LAUTECH Journal of Engineering and Technology 19 (2) 2025: 21-29

10.36108/laujet/5202.91.0230

Influence of Stator Tooth Thickness on Losses and Efficiency of a Double Stator Electric Machine

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Article Info

Article history:

Received: Feb 23, 2025
Revised: May 02, 2025
Accepted: May 03, 2025

Keywords:

Efficiency, electric machine, losses, rotor position and stator tooth.

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ABSTRACT

Owing to the significant impacts of the electric machine's structural dimensions on its output characteristics and values; the effect of stator tooth thickness and shape is considered in this study. Finite element analysis is employed in the predictions. The machine parameters considered are magnetic properties, efficiency, and losses. It is revealed that if the analyzed machine has unequal stator tooth thickness without a stator tooth tip, then the resulting magnetic properties and eddy current loss values would be high; however, with improved overall machine efficiency. Consequently, a similar machine configuration that has equal stator tooth thickness with a stator tooth tip would exhibit larger total loss and a corresponding lower overall efficiency. The predicted magnetic coercive force values of the machine with and without equal stator tooth thickness are: 1415.51 kA/m and 1505.92 kA/m, respectively. Again, the resulting total losses of the machine with and without equal stator tooth thickness are: 19.71 Watts and 19.16 Watts, respectively. Moreover, the improved machine type with unequal stator tooth thickness generated an efficiency of 92.83 % against its counterpart which produced a corresponding efficiency of 92.60 %.

INTRODUCTION

The machine's structural dimensions such as the stator tooth thickness, PM thickness, etc. are influential factors in its output characteristics and values (Sui *et al.*, 2019), including its loss and efficiency worth. This affirmation about the effectiveness of structural dimensions on a machine's output features is reconfirmed by (Gupta and Chaudhary, 2021) and (Awah *et al.*, 2022a and 2022b). Consequently, a machine's loss and efficiency status can be considerably affected by its geometric shapes and dimensions (Dems *et al.*, 2024). Thus, the impact of stator tooth thickness of a dual stator electric machine on its loss and efficiency values is investigated in this current study, to be properly guided on the implications of an adopted stator tooth size and shape on its overall performance.

The size of stator tooth tips amongst other leading design parameters should be considered in the design and optimization of any given electric machine for improved yield, owing to its significant impact on a machine's overall performance, as demonstrated by (Maraví-Nieto *et al.*, 2019). A similar investigation by (Wei and Nakamura, 2020) shows that the performance of a dual stator flux switching machine could be enhanced by introducing unequal stator length in its inner stator segment. The improved machine performance (Wei and Nakamura, 2020) is particularly attributed to its output torque density and flux regulation ability; however, the realization of this feat is partly due to the adoption of the consequent pole magnetization technique.

Loss and efficiency predictions of a double stator machine are developed by (Ma *et al.*, 2022); it is worth noting that the investigation was done using a high superconducting material, which is relatively both expensive and characterized by higher loss content, compared to conventional double stator machines devoid of superconducting materials. It is important to note that the structural plan and operating principle of the developed machine and that of the present investigation are entirely different. By the way, double-stator electric machines usually have larger torque and power densities than their single-stator counterparts; though, with higher mechanical complexities (Asgaria *et al.,* 2022).

Eddy current loss reduction of a multiphase flux-switching machine is proposed by (Luo *et al.*, 2017) through adequate regulation of the system's air gap flux; this flux control is realized by the adoption of a flux barrier, for proper flux control, besides its resulting high thermal management potential. Nevertheless, the eddy current loss reduction analysis was conducted using the analytical method, which is usually characterized by a lower precision level relative to the finite element analysis approach. However, a reasonable amount of simulation time could be saved by applying the analytical method (Ma *et al*., 2022). The machine investigated in this present study is also a flux-switching machine; though, with a double stator structure. Similarly, it is demonstrated that a machine having a high number of poles would ordinarily have large magnetic loss contents, due to the direct relationship between operating frequency and a machine's pole pairs (Mo *et al*., 2018); a double rotor flux-switching machine is used to establish this pole pairs-frequency relation.

Additionally, the core loss reduction of a permanent magnet machine using geometric variable modifications is presented by Soda and Enokizono, 2017. More so, segmentation of either the applied magnets or magnetic cores would reduce the eddy current loss and iron loss components of an electric machine to a reasonable degree, as established by (Yang *et al*., 2020) and (Soda *et al*., 2020), respectively. Nevertheless, great emphasis is usually placed on the magnetization array and direction of the implemented magnet or core materials. Generally, an electric machine that has low loss aptitude would customarily improve the machine's thermal capacity as well as its anti-demagnetization potentials (Zheng *et al*., 2018). However, the demagnetization flaw of a permanent magnet machine is significantly influenced by its quantity of eddy current loss value (Röschner *et al*., 2022).

Implementation of concentrated non-overlapping winding is proven to exhibit more competitive electromagnetic performance compared to its equivalent distributed winding method (Garner and Kamper, 2020); however, at greater core loss penalty, owing to the ensuing higher magneto-motive force (MMF) harmonics. Note that non-overlapping concentrated winding is executed in this current study. Reduced MMF harmonics and improved magnetic isolation are achieved in a machine by utilizing unequal stator tooth thickness, as presented by (Zheng *et al*., 2013). Apart from the minimal MMF harmonics and enhanced magnetic isolation merits; the studies show that other performance metrics such as high winding factor, low amount of eddy current loss, etc. are also obtained through the aforementioned unequal stator tooth arrangement.

It is shown by Li *et al* (2020) that the application of unequal stator tooth thickness of flux-switching electric machine would generally give rise to larger torque and axes inductance, improved efficiency, and relatively lower cost; albeit, at practically higher magnetic loss consequence, in comparison to an equivalent machine that has equal stator tooth thickness.

An improved efficiency is achieved in this study, and to the best of our knowledge; no such investigation and achievement has been carried out nor obtained from double stator electric machine types of Figures 1 models.

This research is subdivided into four (4) Sections. Relevant literature and the background of the study are presented in Section 1. The adopted approach and implemented materials are provided in Section 2. Results and discussion are presented in Section 3; while the concluding remarks are made in Section 4.

MATERIALS AND METHODS

Rare-earth magnets are applied in the compared machine models; however, it should be noted that such magnetic material is relatively higher in price compared to the ferrite-made magnets; though, rare-earth machine exhibits larger energy profile than the ferrite-made counterparts. The predicted copper loss (W_{cu}) of the machine investigated is computed using Eq. (1). Similarly, the iron loss value (W_{iron}) calculated is done through the traditional Steinmetz iron loss expression provided Eq. (2). It is worth noting that the core material in this investigation is steel; however, enhanced output can be achieved from a machine by implementing soft magnetic materials with good mechanical strength (Grande *et al.*, 2018) or by utilizing high-performance amorphous material such as METGLAS (Hreczka *et al.*, 2023). The predicted electrical machine efficiency (η) is expressed in Eq. (3). By and large, this research is studied using the finite element analysis (FEA) technique. The machine has two classifications that is, the machine type that has equal and unequal stator tooth thickness, respectively. It is a double-stator electric machine separated by a dual air gap and a modulating rotor, as depicted in Figure 1. The overall machine length of the machine is 90 mm; it has an air gap length and active stack length of 0.5 mm and 25 mm, respectively. The rated excitation current and applied rotational speed are 15 A and 400 rpm, respectively. It is worth noting that the machine analyzed is a three-phase synchronous machine and uses alternating current. The applied machine parameters are provided in Table 1.

Table 1: Machine parameters

Machine Type	**Original machine**	**Improved machine**
Stator tooth thickness, mm	4.55	4.55 and 4.00
Number of the stator tooth	6	
Pole number	11	
Number of turns	72	
Magnet type	Neodymium	
Magnet Permeability	1.05	
Core material	Steel	
Coil material	Copper	
Coil resistivity	1.68e-008	

Source: (Awah, 2024).

$$W_{cu} = 3I_{rms}^2 R_{ph} \qquad (1)$$

Where: I_{rms} is the root mean square of current and R_{ph} is the phase resistance.

$$W_{iron} = k_h B_{max}^{2 e \frac{3}{2} c_m {}^2 {}_{max}} \qquad (2)$$

Where: k_h, k_e, and k_c are loss constants, f is operating frequency and B_{max} is the peak value of flux density.

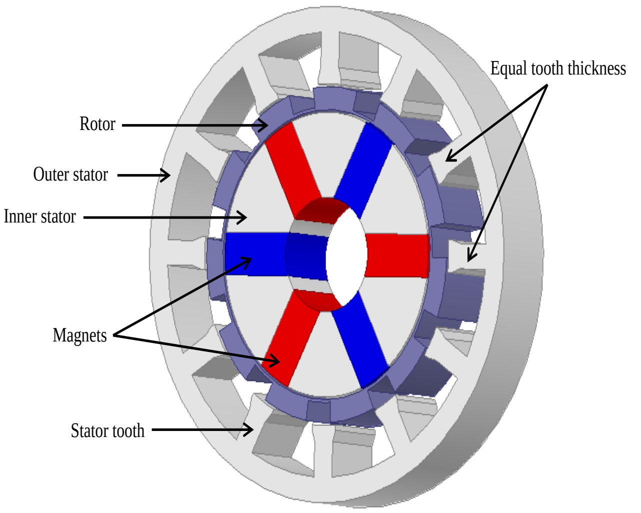
$$\eta = \frac{P}{P + W_{iron} + W_{eddy} + W_{cu}} \% \qquad (3)$$

Where: P is the obtained power, W_{iron} is iron loss, W_{eddy} is eddy current loss due to magnets and W_{cu} is copper loss.

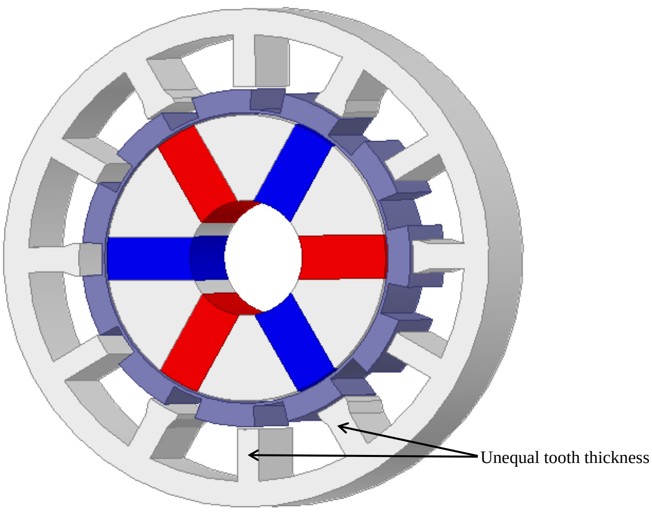
The computed loss values are indirectly proportional to the resulting machine's overall efficiency. Meanwhile, the magnetic coercive force is obtained using the traditional *B-H* curve expression, given in Eq. (4). Note that the magnetic coercive force component of a machine is a direct function of its magnetic field strength.

$$B = \mu H \tag{4}$$

Where: B is the magnetic flux density measured, in Tesla and H is the magnetic field strength, measured (AT/m).



(a) Original machine having equal stator tooth thickness (Awah *et al.*, 2016)



(b) Improved machine having unequal stator tooth thickness

Figure 1: The analyzed machine diagrams

RESULT AND DISCUSSION

Figure 2 shows the core loss density distribution of the compared machine types. It is observed that the intensity of the core loss is higher at the stator tooth and rotor tip regions. This implies that these two regions are most likely to undergo electromagnetic saturation quicker than other parts of the machine; thus, their exposure to excessive electric loads should be taken into consideration. The magnetic properties of the investigated machine are presented in Figure 3. Larger magnetic remanence and coercive force values are obtained from the improved machine; these higher magnetic property values would consequently influence the other electromagnetic outputs of the machine positively.

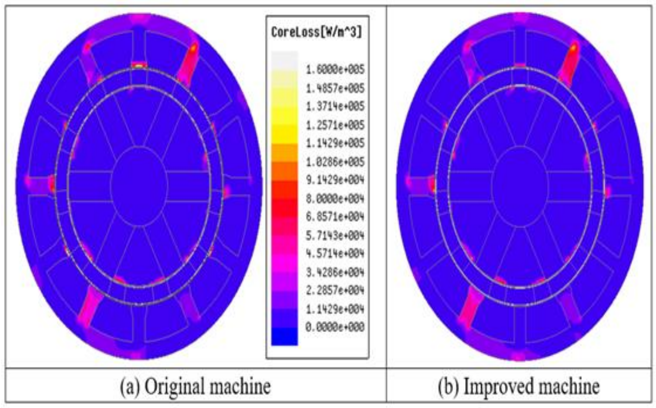
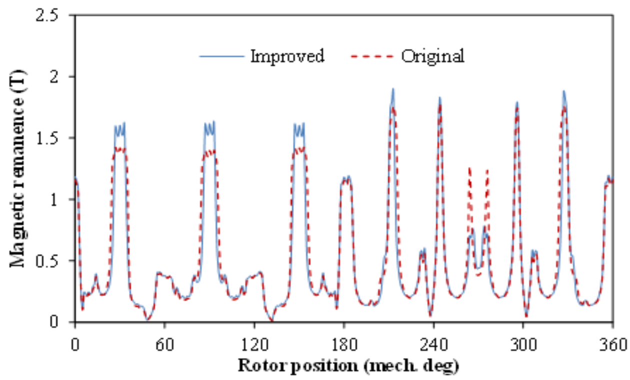
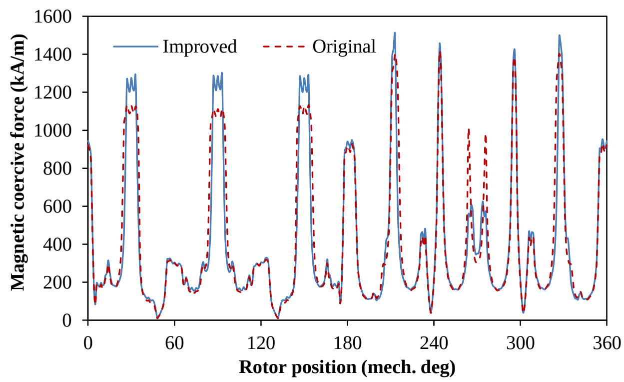


Figure 2: Core loss contour at rated current: (a) Original machine (b) Improved machine



(a) Magnetic remanence versus rotor position

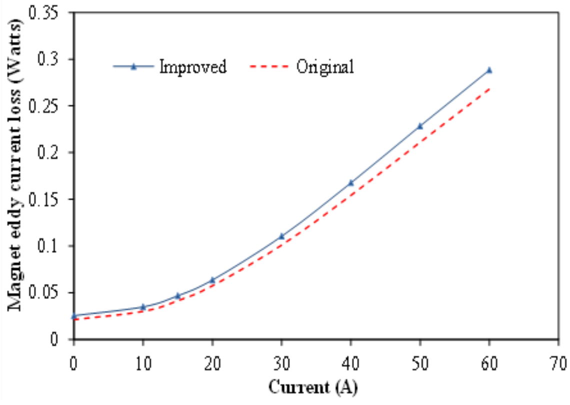


(b) Magnetic coercive force versus rotor position

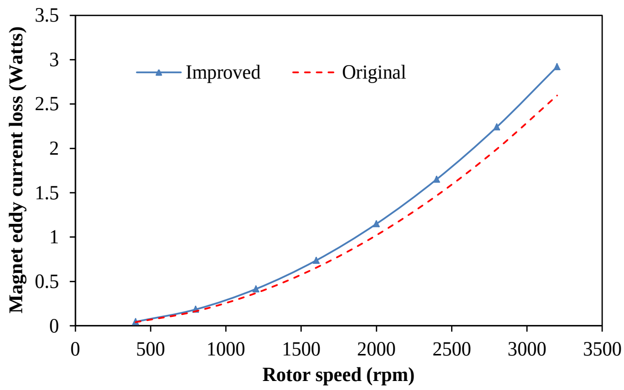
Figure 3: Comparison of magnetic properties

Eddy current losses due to the excited magnets are depicted in Figure 4. The original machine type has lower eddy current loss compared to the improved machine type, in all the simulation conditions. It is observed that the predicted eddy current loss increases with an increase in both current and speed, as presented in Figure 4 (a) and 4 (b), respectively. The variation of eddy current loss over one electric revolution is uniformly distributed, as shown in Figure 4 (c). Iron loss values of the compared machine are reasonably similar; though, with a slightly lower magnitude by the improved machine, as provided in Figures 5 and 6. Again, the iron loss values of the investigated machine types increase exponentially with a rise in applied current, while its loss variations in one electric period are evenly distributed over the simulated rotor positions. It is important to note that the obtained lower loss content of the improved machine type is essential in enhancing its overall efficiency. The estimated iron losses of both the rotor and stator cores are obtained using the mathematical expression of Eq. (2).

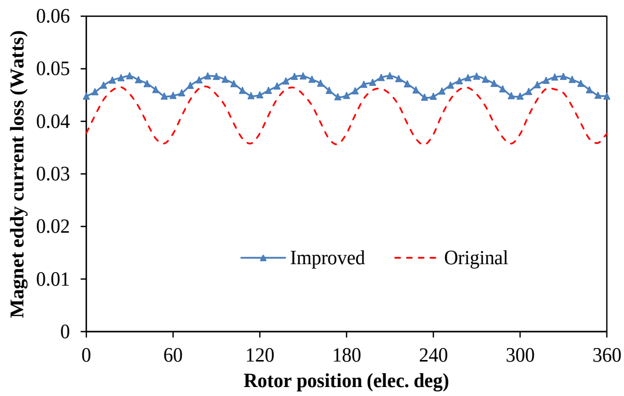
It is important to note that the models of Figure 1 of the machine types investigated are simulated over one electric cycle, which starts from no-load to full-load conditions. Meanwhile, the simulation's starting and finishing time corresponds to the 0 and 360 electrical degree points of an electric cycle, respectively, and hence, of the machines' rotor positions. These and other points/rotor positions are estimated via interpolation procedures.



(a) Magnet loss versus current

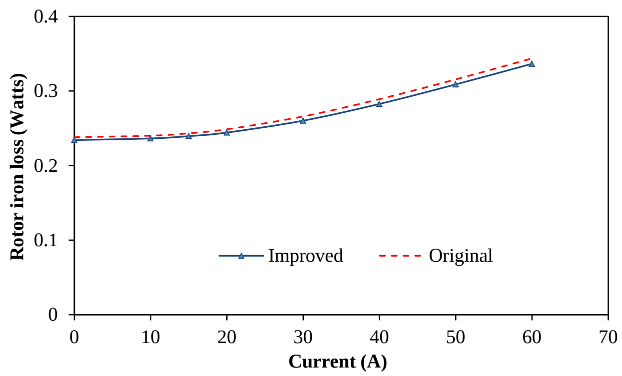


(b) Magnet loss versus speed

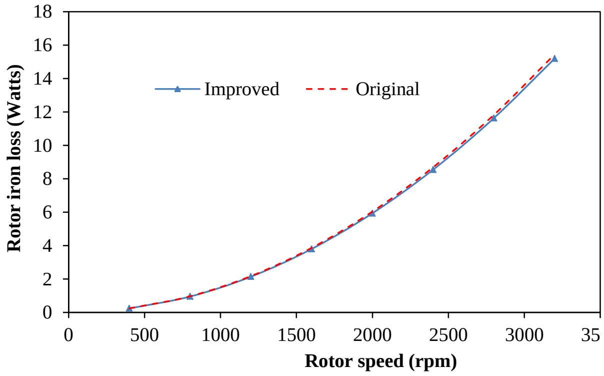


(c) Magnet loss versus rotor position

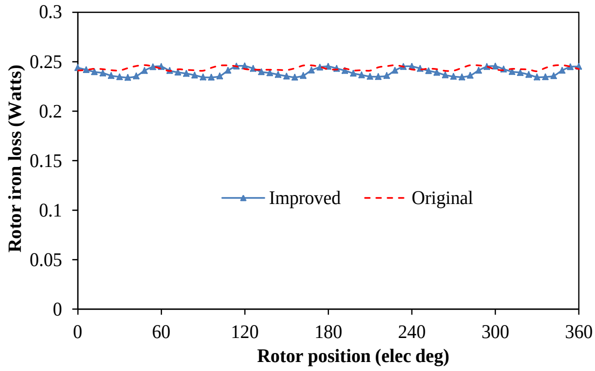
Figure 4. Magnet eddy current loss variations



(a) Rotor iron loss versus current

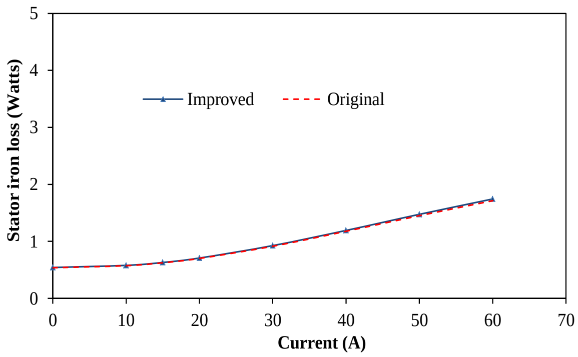


(b) Rotor iron loss versus speed

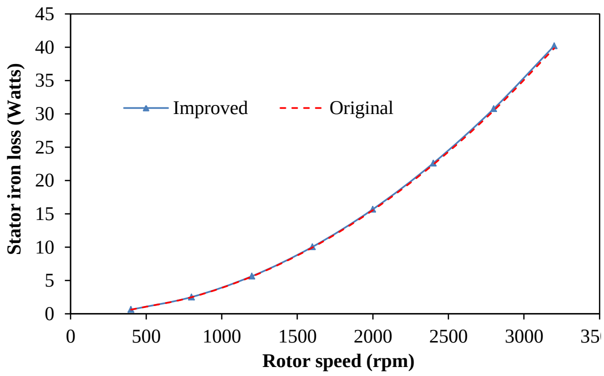


(c) Rotor iron loss versus rotor position

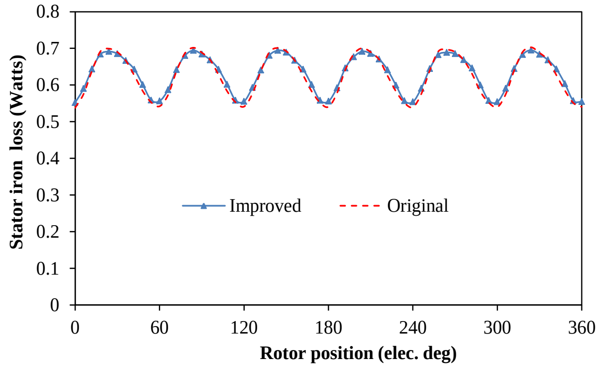
Figure 5. Rotor iron loss variations



(a) Stator iron loss versus current



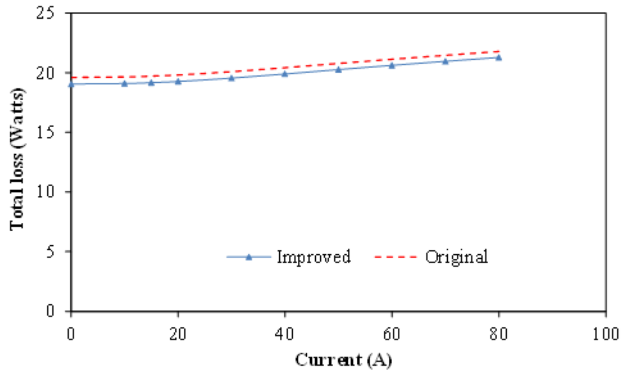
(b) Stator iron loss versus speed



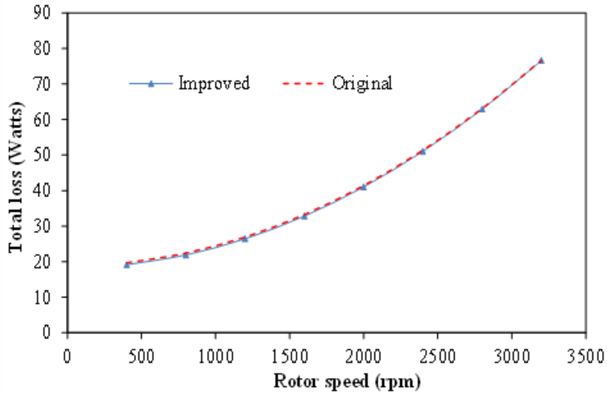
(c) Stator iron loss versus rotor position

Figure 6. Stator iron loss variations

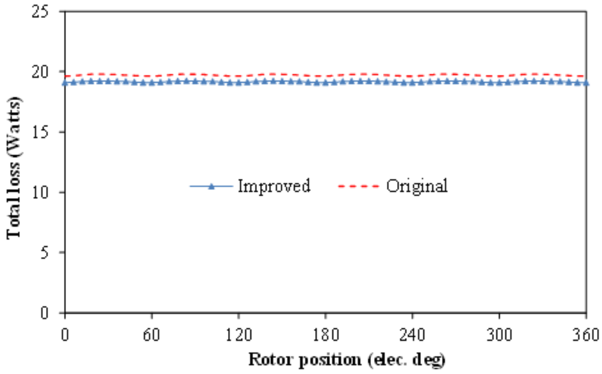
The original machine type exhibited a higher amount of total loss in all simulation circumstances, as shown in Figure 7. The lower total loss value of the improved machine type is an advantage over its compared equivalent machine; considering its great impact on the electrical efficiency of a machine. Meanwhile, the estimated copper loss values of the investigated machine at rated operating speed and current are: 18.25 W and 18.80 W i.e. for the machine that has unequal and equal stator tooth widths, respectively.



(a) Total loss versus current



(b) Total loss versus speed



(c) Total loss versus rotor position

Figure 7. Magnet eddy current loss variations

The efficiency of the machine categories investigated is displayed in Figure 8. The improved machine type is shown to have greater efficiency than its counterpart. Maximum efficiency occurred at a high speed of about 2000 rpm. The predicted efficiency of the compared machine types having equal stator tooth thickness (original machine type) is 92.60 % while its counterpart that has unequal stator tooth thickness (improved machine type) yielded an efficiency of 92.83 %.

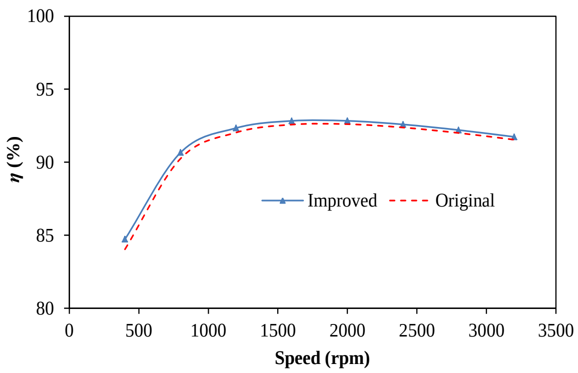


Figure 8. Efficiency comparison

CONCLUSION

Loss and efficiency predictions of a dual stator electric machine are presented and quantitatively compared, considering the impact of its stator tooth thickness. The finite element approach is implemented in the analysis, due to its inherent high precision level. It is revealed that a machine that has unequal stator tooth thickness would have a corresponding larger magnetic coercive force as well as improved overall machine efficiency compared to its counterpart that is equipped with equal stator tooth thickness; though, with a resulting higher amount of eddy current loss. Nevertheless, the predicted total loss is higher in the machine category that has equal stator tooth thickness, which is a shortcoming. The study will serve as a guide on electromagnetic implications of stator tooth geometric sizes and shapes, of electrical machines.

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