Nigerian Journal of Engineering, Vol. 29, No. 2, August 2022, ISSN (print): 0794 – 4756, ISSN(online):2705-3954.

Nigerian Journal of Engineering,
Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria
journal homepage: www.njeabu.com.ng

Loss and Efficiency Comparisons of Permanent Magnet Machine Having Double Stator Structure

C. C. Awah
Department of Electrical and Electronics Engineering, Michael Okpara University of Agriculture, Umudike, PMB 7267, Umuahia, Abia State, Nigeria
awahchukwuemeka@gmail.com

Research Article

Abstract

Loss quantity and efficiency profiles of a double stator permanent magnet machine (DSPMM) would be studied. The considered loss components are: Magnet eddy current loss, rotor iron loss, stator iron loss and total loss; undertaken at varying load current, rotational speed and rotor angular position. Additionally, the effect of different rotor pole numbers on loss and efficiency values of the investigated DSPMM would also be presented. The predicted results are estimated with Maxwell-2D version 15.0 simulation software, using finite element analysis method. The results show that both the electric load and motor speed, in addition to the machine's pole number, would influence the resultant amount of loss and efficiency in the machine. Meanwhile, the resulting amount of total loss in the system would be proportional to the implemented pole number i.e. the higher the pole number, then, the larger the resulting total loss value. The predicted total loss of the machine at a rotating speed of 3200 rpm is approximately equal to 84.70 W, 84.78 W, 88.05 W and 89.91 W, respectively from the compared 10-pole, 11-pole, 13-pole and 14-pole machine topologies. The machine's efficiency at rated speed and current is: 81.38 %, 89.27 %, 88.58 % and 83.10 %, i.e., from the considered respective pole numbers.

Keywords
Current; efficiency; loss; rotor angular position; speed.

Article History
Received: March, 2022
Reviewed: April, 2022
Accepted: May, 2022
Published: August, 2022

1. Introduction

Electromagnetic loss in any electrical machine gives rise to increased temperature and reduced efficiency in such system; therefore, adequate assessment of different kinds of loss in the system is paramount for efficient and effective machine operation, as deduced from Du *et al*, (2020). Thus, the loss and efficiency comparisons of a given dual stator permanent magnet machine is evaluated in this work, for proper guide to electrical machine designers on the direct consequence of loss components on the overall machine efficiency. The cumulative effect of loss components of the analyzed machine category is summarized as thus: the higher the machine's pole number; then, the larger the resulting total loss value from the system. Moreover, resultant loss values due to the pole number effect would also rely on the machine's load current, speed and inherent harmonic impact/output torque magnitude of the implemented poles. All these influencing factors would invariably affect the resulting efficiency of the machine. Meanwhile, these consequences are worsened in situations where the machine's output performance is to be maximized, as noted in (Al-Timimy *et al.*, 2018).

More so, the eddy current loss in an electric machine could result to lower electromagnetic performance of the machine and may eventually lead to system failure/breakdown, owing to the potential subjection of the system to demagnetization effects (Chiodetto *et al*, 2017). Wang *et al*, (2022) further pointed out that increased temperature outcome of a given electrical machine could cause adverse effects such as magnet demagnetization and poor electromagnetic output, which may result to total machine collapse, if not controlled. Additionally, it is reconfirmed in Ma and Zhu (2019) that the eddy current loss of a permanent magnet machine could be considerably large at high operating speed and could intensify the machine's thermal instability; besides its high tendency for irreparable demagnetization and system degradation. Though, significant loss reduction could be achieved through adequate optimization of the stator geometry having subsidiary slots, in order to reduce the generated harmonics in the machine, and hence, lessen the resultant eddy current loss in the device.

Similarly, the overall power loss of a system could be reduced in an electric machine by adopting adequate Pulse Width Modulation scheme, through appropriate control of its fundamental and switching frequencies; particularly, for systems that are excited by wide-band gap inverters (Chang *et al.*, 2021). However, such a control technique may likely introduce more undesirable harmonics due to switching effects of the power electronic devices. Nevertheless, it is established in Yamazaki *et al*, (2019) that loss contribution due to harmonics in an electrical machine could be decreased substantially, through proper optimization of the machine's core structures without sacrificing other electromagnetic output performance (s) of the machine.

Meanwhile, the nature of excitation and its resulting harmonics effect should be taken into cognizance in analyzing the loss profiles of electrical machines; since, these factors could heighten the core loss level in such systems. Thus, an improved analytical loss model considering the harmonic elements as well as the magnetization phase angle and amplitudes is proposed in Zhu *et al*, (2021); however, with some slight inaccuracies on the results, due to the attendant precision problems of analytical model estimations.

Also, adequate implementation of control management and mechanism of a machine's magnetic excitation mode using alnico and neodymium-iron-boron (Nd-Fe-B) magnets; especially, at constant power or flux-weakening operating region of the machine, could drastically minimize the system losses and thus, enhance the overall efficiency (Xu *et al*, 2021) of the machine. Basically, the loss reduction strategy presented in Xu, *et al*, (2021) is achieved through combined effect of the above two mentioned magnets having varying degree of magnetic coercivity and residual magnetic flux density; and this would have direct implication on the resulting induced-voltage of the machine. Note that the implemented magnet type in this current study is of the Nd-Fe-B category, though loss reduction study is not investigated.

Further, it is established in (Yamazaki *et al.*, 2017) that the core loss in an electrical machine as well as the corresponding output torque is influenced by the machine's level of mechanical pressure or stress. More so, the impact of this mechanical pressure on the machine performance is worsened at high operating speed, due to the great influence of forces on the system at such operating conditions. The influence of pressure on the loss profile of a given electrical device is also highlighted in (Grande *et al.*, 2018); although, the use of improved soft magnetic core materials in an electrical device could reduce both the cost and loss amplitude of the system compared to the use of standard or conventional silicon steel materials. However, the use of some high-grade silicon steel materials such as A470 and A1300 would yield reasonable efficiencies in the device; albeit, at higher cost outcome. Silicon steel material is adopted in this present investigation.

Furthermore, the investigated machine in this present study is adopted as a motor instead of a generator; nevertheless, its generator mode would be feasible through appropriate interchange of the machine's winding terminals. Although permanent magnet synchronous motors (PMSM) and permanent magnet synchronous generators (PMSG) exhibit different output characteristics; however, they could have similar design procedures and may equally be applied in direct drive uses, as could be inferred from Alemi-Rostami *et al*, (2022). It is worth noting that the analyzed machine in this present investigation is a synchronous motor.

In essence, this present study would estimate the loss and efficiency magnitudes of a double stator permanent magnet machine with the help of finite element analysis software, in order to have insight on the overall effect of losses on the efficiency of the investigated machine considering its varying number of rotor poles. The resulting total loss value of the system is a direct product of the adopted machine's pole number, rotor speed and applied load, at any given simulation instance.

2. Methodology

Maxwell-2D version 15.0 is adopted in the loss and efficiency calculations, using 2D-finite element analysis (2D-FEA) method. The analyzed double stator permanent magnet machine diagram is given and labelled in Figure 1. The considered loss constituents in this study include: permanent magnet eddy current loss, copper loss, stator and rotor core losses. In the finite element analysis (FEA), transient solver solution type is selected for improved electromagnetic outcomes. Moreover, the following excitations and settings were assigned to the different sections of the machine:

Coil section

Excitation type: Current mode having stranded conductors

Permanent magnet section

Excitation type: Eddy effects having zero current amplitude

Stator and rotor sections

Excitation type: Core loss settings

Boundaries

Excitation type: Vector potential having zero flux per unit metre

Rotor periphery (Band) section

Model settings: Motion setup having angular/rotational velocity

Optimetrics constraint

Parametric setup: Linear speed step and range [400:400:3200]

It is worth noting that the assumed initial angular rotor position (R_i) in this study corresponds to the maximum flux linkage point on open-circuit condition and is obtained using the expression in equation (1).

$$R_i = \frac{\alpha_{dq}}{P} \tag{1}$$

Where P is the machine's pole number and α_{dq} is the angular difference between the machine's direct and quadrature axis paths.

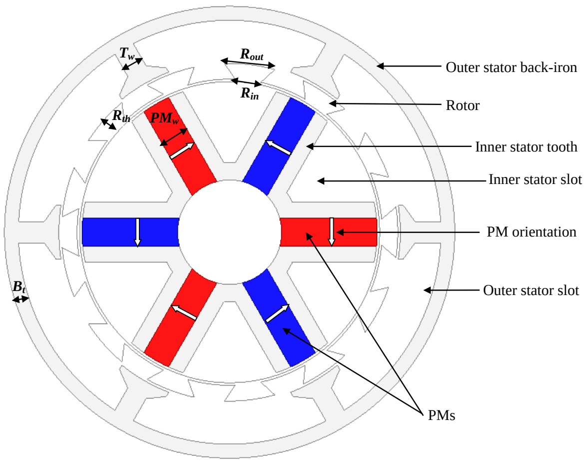


Figure 1: Analysed machine diagram having 13 pole number (Awah *et al*, 2022).

It is worth noting that the rotor and stator core sections of the investigated machine topologies are made of silicon steel material while the magnets are of rare-earth material with high energy product, containing neodymium magnetic material having a residual flux density (B) of 1.2 Tesla and magnetic coercive force (H) of -909,456.82A/metre. It is worth mentioning that the adopted FEA software generates the numerical results automatically using the investigated Figure 1 model, in relation to the inputted corresponding electromagnetic loadings. Note also that the adopted magnet has relative permeability of 1.05. More so, the implemented B-H curve of the steel cores is displayed in Figure 2. Note also that the analysed machine is a three-phase system. Thus, the predicted FEA efficiency (η) of the machine is obtained from the mathematical expression in equation (2). Moreover, the estimated core loss (P_{fe}) in the system is predicted using equation (3). Basic parameters of the analysed machine model are listed in Table 1.

$$\eta = \frac{P_{out}}{P_{out} + P_{cu} + P_{fe} + P_e} \times 100 \tag{2}$$

where: P_{out} is the output power, P_{cu} is the copper loss, P_{fe} is the core loss and P_e is the eddy current loss due to the magnets.

$$P_{fe} = k_h B_{\max}^2 f + k_a (B_{\max} f)^{1.5} + k_e (B_{\max} f)^2 \tag{3}$$

where: f is the operating frequency, B_{max} is the maximum flux density, k_h is the hysteresis constant, k_a is the excess loss constant, k_e is the eddy current constant (Liu *et al*, 2018).

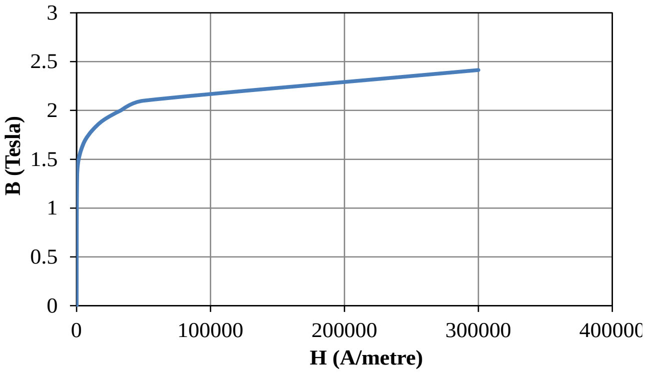


Figure 2. The implemented B-H curve.

Table 1: Machine parameters

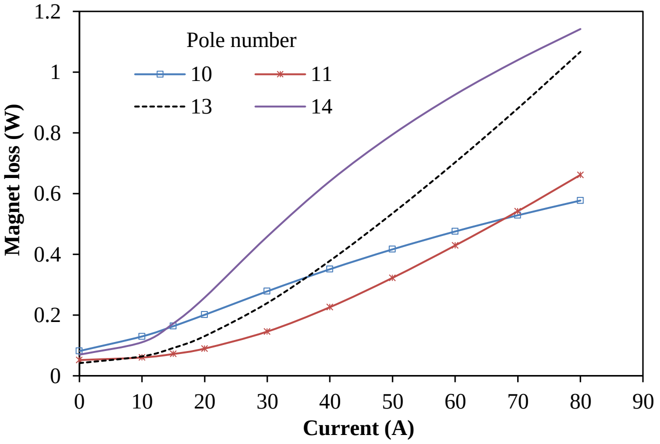
Item	Value
Inner stator pole	6
Outer stator pole	6
Air-gap length	0.5 mm
Machine's stack length	25 mm
Machine radius	45 mm
Machine's flux density	1.2 Tesla
Winding factor	0.6
Magnet brand	N35SH
Core material	Silicon steel
Rated current	15A
Number coils per phase	2
Working temperature	22ºC
Rated speed	400 rpm

3. Losses

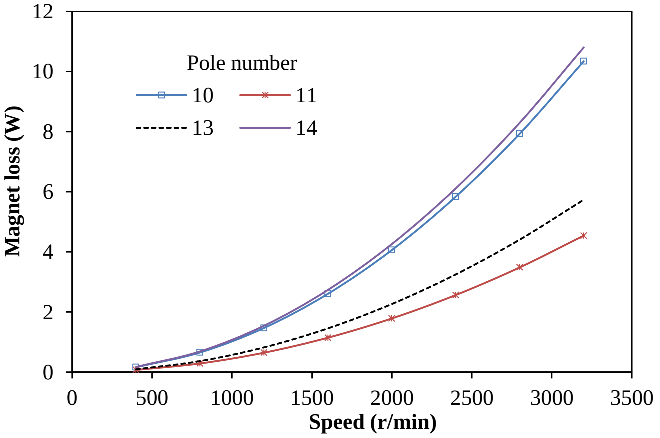
Loss assessment in the various parts of the machine such as the eddy current loss in the magnets, core losses in the rotor and stator are presented in this section. Figure 3 depicts the eddy current loss in the magnet as a function of electric load current, rotor speed, rotor angular position and pole number variations. Under the rated current of 15 A and rated speed of 400 rpm, the machine types having odd number of rotor poles seem to exhibit lower amount of eddy current loss compared to the ones having even number of rotor poles, as shown in Figure 3 (a). However, this trend is not maintained at higher electric loading due to the effect of armature reaction of the windings; and hence, the resulting saturation impact. Similarly, Figures 3(b) and (c) show that the 11-pole and 13-pole machine types have lower magnitude of eddy current loss, compared to the 10-pole and 14-pole types. More so, the magnet eddy current loss in the machines would vary exponentially with both the motor/rotor speed and the applied electric load. Meanwhile, the resulting amplitude of magnet eddy current loss is also dependent upon the rotor angular position, as shown in Figure 3(c). In particular, electrical machine that has high energy density magnetic materials such as neodymium-iron-boron (Nd-Fe-B) would have higher negative influence on both the machines' eddy current loss and overall efficiency, owing to its high conductivity values, as presented in Tsunata, (2018). Nevertheless, a reduced loss and improved efficiency can be obtained from an electrical machine by segmentation of the magnets, as demonstrated in Al-Timimy *et al*, (2018).

Further, rotor iron loss variations with current, motor speed and rotor angular positions are shown in Figure 4. Again, the iron loss magnitudes vary exponentially to the electric current load and motor speed.

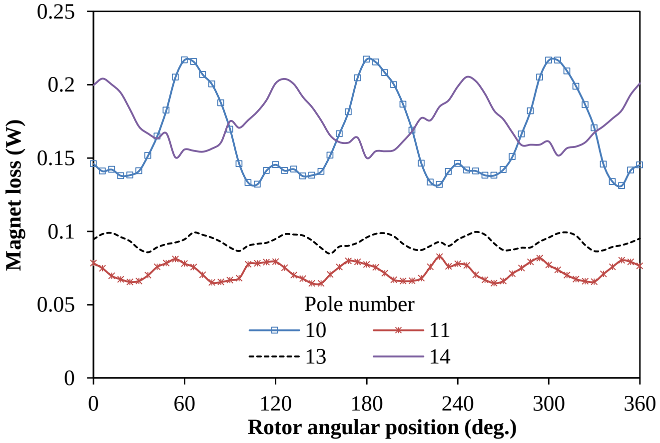
Moreover, the machine types having odd number of poles have larger amount of losses compared to their counterparts that are equipped with even number of poles; likely due to the its high space harmonic elements. It is essential to note that the investigated double stator permanent magnet machine in this current study is a class of FSPM machine. More so, the number of cycles in the machine types that have odd number of poles is twice that of the machines having even number of poles, because the electromagnetic waveforms and its resulting number of cycles of electrical machine is a function of the machine's stator and rotor pole arrangements, in addition to the lowest common multiple (LCM) between these pole arrangements, as inferred from Chen and Zhu, (2010) and Wu *et al*, (2014). More so, other factors such as armature reaction, inductance value and periodicity (Fornasiero *et al*, 2012; Jun *et al*, 2017) would also affect the resultant loss output of a given electric machine.



(a) Magnet loss versus current

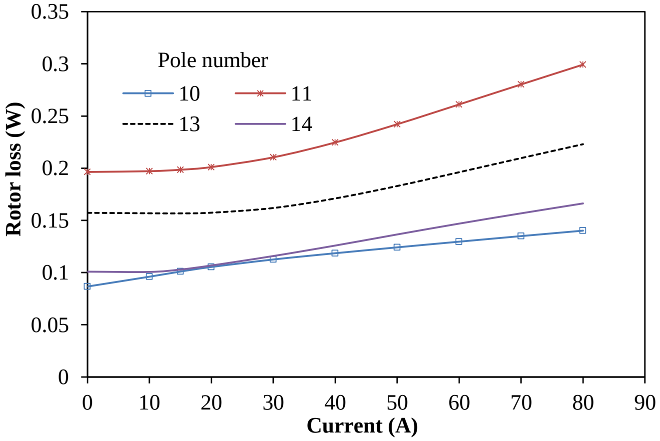


(b) Magnet loss versus speed

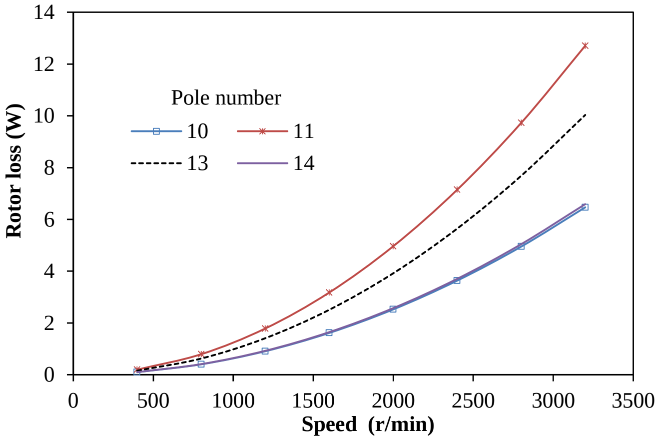


(c) Magnet loss versus rotor angular position

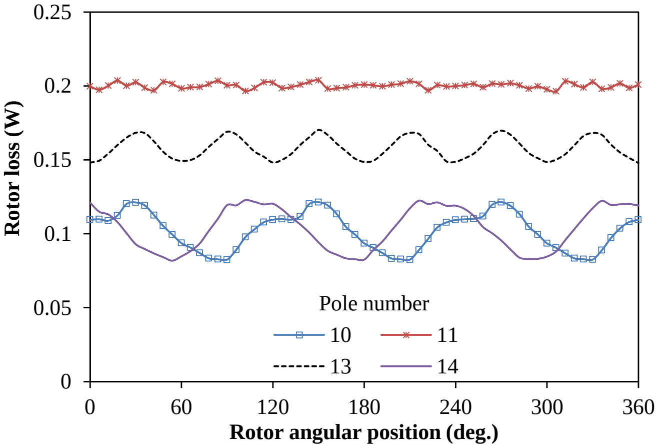
Figure 3. Comparison of magnet eddy current loss.



(a) Rotor iron loss versus current



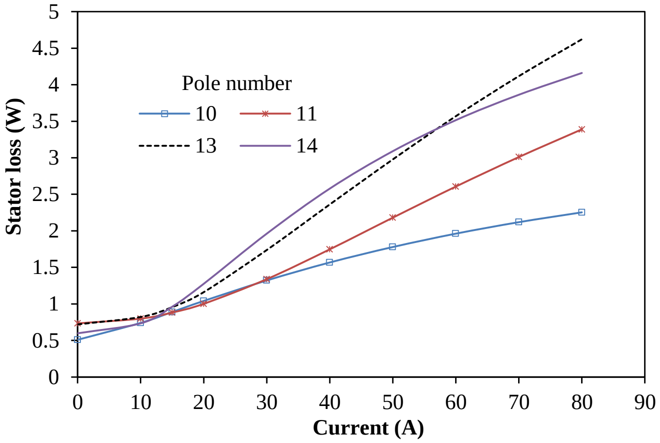
(b) Rotor iron loss versus speed



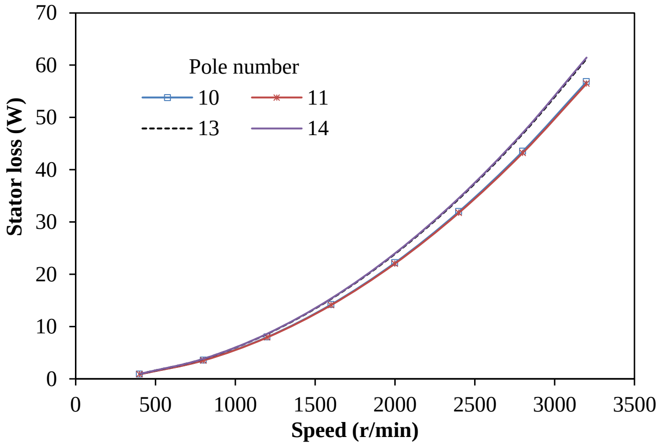
(c) Rotor iron loss versus rotor angular position

Figure 4. Comparison of rotor core loss.

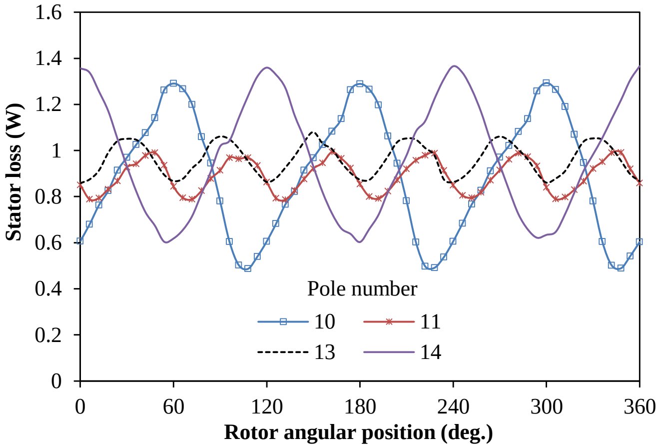
Similarly, the stator iron loss variation with current, speed and rotor angular position is depicted in Figure 5. The results show that there is a non-linear relationship between the produced iron loss values, electric load and speed. Moreover, it could be observed that the generated stator iron loss in the system is dependent upon the number of rotor poles. Since, the frequency of the investigated machine is a function of its rotor pole number; hence, the higher the pole number, then, the larger the iron loss magnitude in the machine, and vice-versa. More so, the stator iron loss outlines of Figure 5(c) shows that the machine types having even number of rotor poles have high amount of loss ripples, most likely due to its high harmonic contents. Meanwhile, the amount of harmonics in a system could aggravate its iron loss or core loss magnitude, as recorded in Yu *et al*., (2019). Also, the produced iron loss would depend upon the rotor angular position at any given time.



(a) Stator iron loss versus current



(b) Stator iron loss versus speed

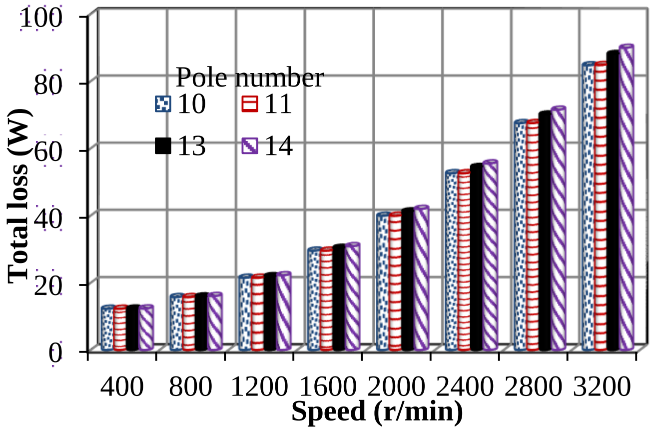


(c) Stator iron loss versus rotor position

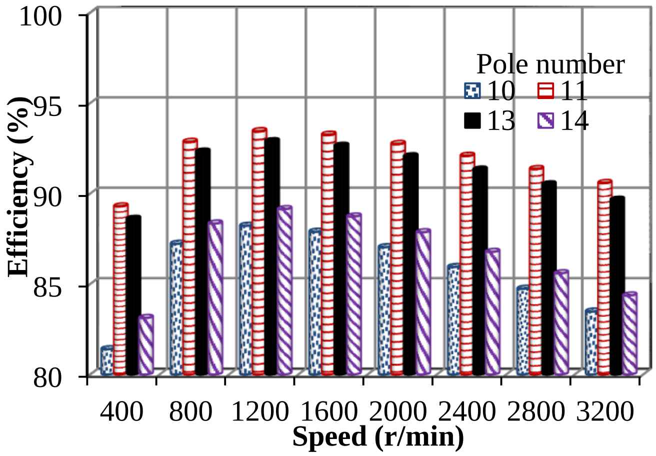
Figure 5. Comparison of stator iron loss.

4. Efficiency

The total loss in the investigated machine include: the sum of rotor and stator iron losses, copper loss and eddy current loss due to magnets. The predicted total loss in the system is displayed in Figure 6 (a). It is observed from Figure 6 (a) that the total loss in each of the considered machine configurations is seemingly equal at a particular working speed, except at higher operating speed; possibly, due to the counteractive impact of copper loss on an increasing motor speed, unlike the reverse effect from both the iron loss and mechanical loss on the operating motor speed, as detailed in Toulabi *et al*, (2017). Further, the estimated efficiencies of the compared machine types are presented in Figure 6(b). At all the operating speed settings, the machine types having 10-pole number exhibit the worst efficiency aptitude, followed by its 14-pole counterpart. Meanwhile, the most promising efficiency is exhibited by the machine types having odd number of rotor poles, particularly the 11-pole machine. The efficiency gotten from the 10-pole, 11-pole, 13-pole and 14-pole machine topologies under rated load and speed conditions is: 81.38 %, 89.27 %, 88.58 % and 83.10 %, respectively. Moreover, the efficiency of a given permanent magnet machine is shown to be higher at relatively lower current density, according to the reported results in Zhao *et al*, (2017); though, with dependency on the rotor and stator pole combinations of the machine. Electrical machines that have very high pole number would suffer from poor efficiency skill, due to its electrical frequency, which tends to affect the machines significantly and negatively, especially at high-speed operation (Zhao *et al*, 2017).



(a) Total loss versus speed



(b) Efficiency versus speed

Figure 6. Comparison of loss and efficiency.

5. Conclusion

Loss and efficiency profiles of a double stator permanent magnet machine having different rotor pole numbers is investigated and presented. The results reveal that the predicted loss components would rise with increasing speed and electric current load. More so, the resulting loss values would depend on the rotor angular positions. Besides the influence of both rotor speed and load current; the obtained total loss magnitudes of the analyzed machine is seen to be a direct consequence of the adopted pole number; i.e. the higher the pole number, then, the larger the total loss values. The obtained efficiency of the machine at rated operating conditions of 400 rpm and 15 A is: 81.38 %, 89.27 %, 88.58 % and 83.10 %, respectively, from the considered machine having different pole numbers (i.e. from the 10-pole, 11-pole, 13-pole and 14-pole machine configurations).

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