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Loss and efficiency profiles of double stator permanent magnet machine

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Abstract
Loss estimation of double stator permanent magnet machine is predicted in this study using finite element method. The influence of rotor speed, electric loading and stator/rotor pole combinations of the investigated machine is also quantified and compared. It is revealed that the machine types with odd number of rotor poles have larger iron loss values than their even rotor pole number counterparts. Moreover, the efficiency of the analyzed machine categories is also presented with the machine types having odd number of rotor poles taking the lead in efficiency profiles amongst all, owing to its larger output torque and power. The predicted peak efficiency of the compared machine types (i.e. the 10-, 11-, 13- and 14-pole machines) operated at 400 rpm is: 76.70 %, 86.88 %, 86.23 % and 79.92 %, respectively. Nevertheless, compared machine types have comparable overall loss values at rated load and machine speed of 400 rpm.

Keywords: Efficiency, permanent magnet machine, rotor and stator iron losses.

1. Introduction

The iron loss and copper loss of electric machines constitute significant portion of the total loss in such systems; though, it is reported in Soda *et al*., (2021) that iron loss of a given permanent machine could be reduced by use of modular stator core in such a way that the core's magnetization path would align with that of stator radial formation; further loss decrease would be achieved if the base end of the stator teeth is optimized for improved winding packing factor. Nevertheless, the above assertion needs to be verified at least by test results. More core loss reduction could be obtained in an electric machine through the use of improved steel materials characterized with low loss substances particularly the permeability, as demonstrated in Yamazaki *et al*., (2018). However, the effectiveness of most grades of the steel materials would depend on the involved cutting, punching and fabrication processes, as inferred from Bourchas *et al*., (2017) and Tan-Kim *et al*., (2017); since, these processes tend to introduce some level of mechanical inaccuracies in the loss estimation due to tolerance flaws; though, improved steel grades such as 10JNEX900 (Widmer *et al*., 2014) would reduce the resulting iron loss in a given electrical machine; additionally, it could help to enhance the consequential low mechanical stability of the machines (Ou *et al*., 2021) as better alternative to other soft magnetic composite (SMC) materials. Conversely, the choice of any material would depend on its specific application(s), since the properties of these materials differ, and this may thus lead to selection compromise.

Similarly, the copper loss value in an electrical device would be a function of its supplied root-mean-square current and phase resistance of the stator windings. More so, eddy current loss of electric machines would also have negative effect on efficiency of the system. It is pointed out that the use power electronic and switching devices could intensify the eddy loss amplitude in an electrical machine to almost one-half of the total eddy loss value (Chang *et al*., 2020). It is worth noting that temperature impact could be considerable high on the resultant iron loss magnitude of an electrical machine, as stated in Zhu *et al*., (2019). Moreover, the accuracy of loss models is usually dependent on factors such as its flux density components, operating temperature and harmonics from adopted power electronic gadgets; however, loss prediction using finite element analysis would always yield higher accuracy, though with increased simulation time compared to analytical predicted results of the models.

The effect of harmonics on iron loss of an electrical machine is usually high in the constant power region owing to the increased value of direct axis current at such operating points. Further, the efficiency outlines of electrical machines could be predicted with approximate mathematical expressions of torque, power, rotational speed and load, as established in Kahourzade *et al*., (2020) using exponential fitted curves. Also, the need for accurate prediction of the iron loss, flux linkage and their dependence on cross-coupling/saturation effects of both direct- and quadrature-axes currents cannot be overestimated, due to its significant impact on machine efficiency.

Dmitrievskii *et al*., (2019) demonstrated that the efficiency of permanent magnet machine could be enhanced by an appropriate reduction of its slot number with a corresponding increase in the winding slot areas for an improved winding packing factor. Further, the overall performance of such machine would be boosted through adequate reduction of the machine's torque ripple and total harmonic distortion values, usually done at the optimization stage. Furthermore, the adoption of grain-oriented magnetic materials could also improve the efficiency of the system following the resulting iron loss, conductor loss and anomalous loss reductions, as proved in Mallard *et al*., (2019) with additional insulation capacity, especially when the rotor sections are made with die-cast copper materials. However, these improved machine efficiency and performance usually comes with high economic implications compared to the conventional machines without these features. Moreover, it is proved in Fu *et al*., (2020) that the efficiency of a given permanent magnet machine owing to pulsating current could be improved by counteracting the current pulses with corresponding increase in machine's inverter changing frequency.

It should be noted that losses due to harmonics could negatively affect the performance of the machine, particularly, on parameters such as the efficiency, torque undulation, noise and its consequent vibration effects, as highlighted in proposed analytical studies in Balamurali *et al*., (2021). However, the use of suitable current advance angle to control these harmonic effects, which tends to also interfere with the flux density of the machine could considerably reduce the losses and subsequently enhance the machine's efficiency. In as much as the reported analytical loss reduction and improved efficiency prediction methods in Balamurali *et al*., (2021) has reasonable accuracy compared to most existing methods in literature; the analytical means of performance prediction usually has less precision ability compared to finite element analysis.

Since, all the above-mentioned machine losses would affect the overall efficiency in the system; therefore, the iron loss, copper loss, and eddy current loss characteristics of double stator permanent magnet machine having different number of poles is investigated and presented in this current study, in order to evaluate its efficiency standing and proffer possible means of improvement for enhanced machine performance. This investigation is subdivided as follows: Introduction; methodology; results and discussion and conclusion.

2.0 Material and methods

The estimated iron and eddy current loss results in this work are obtained using MAXWELL-2D computational software; however, the copper loss and efficiency values are predicted using mathematical expressions stated in this section. If the machine data provided in Table 1, is inputted in the computer models of Figure 1; then, the employed software would automatically generate the iron and eddy current loss results of the analyzed models. The computer-generated results are usually obtained from the transient to the steady-state operational time limits of an electrical period. Figure 1 shows the core loss density of the investigated machine. It is observed that the outer stator back-iron of the machine and some parts on the inner stator which has close proximity to the air-gap region would have high risk of saturation. This saturation-risk sign is higher in the machine topologies with odd rotor pole number. The loss simulation is conducted on steady state condition with refined mesh elements on the entire surface of the model. Similarly, the prediction of copper loss (W_{cu}) value is realized from equation (1). Meanwhile, the phase resistance of conductors in a given electrical machine is temperature-dependent, as seen in equation (2). Further, the predicted efficiency expression is stated in equation (3). The considered loss quantities are: magnet eddy current loss, iron loss, and copper loss. It is important to note that frictional and windage losses are omitted in this study, owing to restriction on the adopted method. The data of analyzed models are listed in Table 1. Note that "P" in this work designates the number of rotor pole i.e. 10P stands for 10 rotor pole number. All the analyzed models have same number of turns, same excitation current and same size, for fairness sake.

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

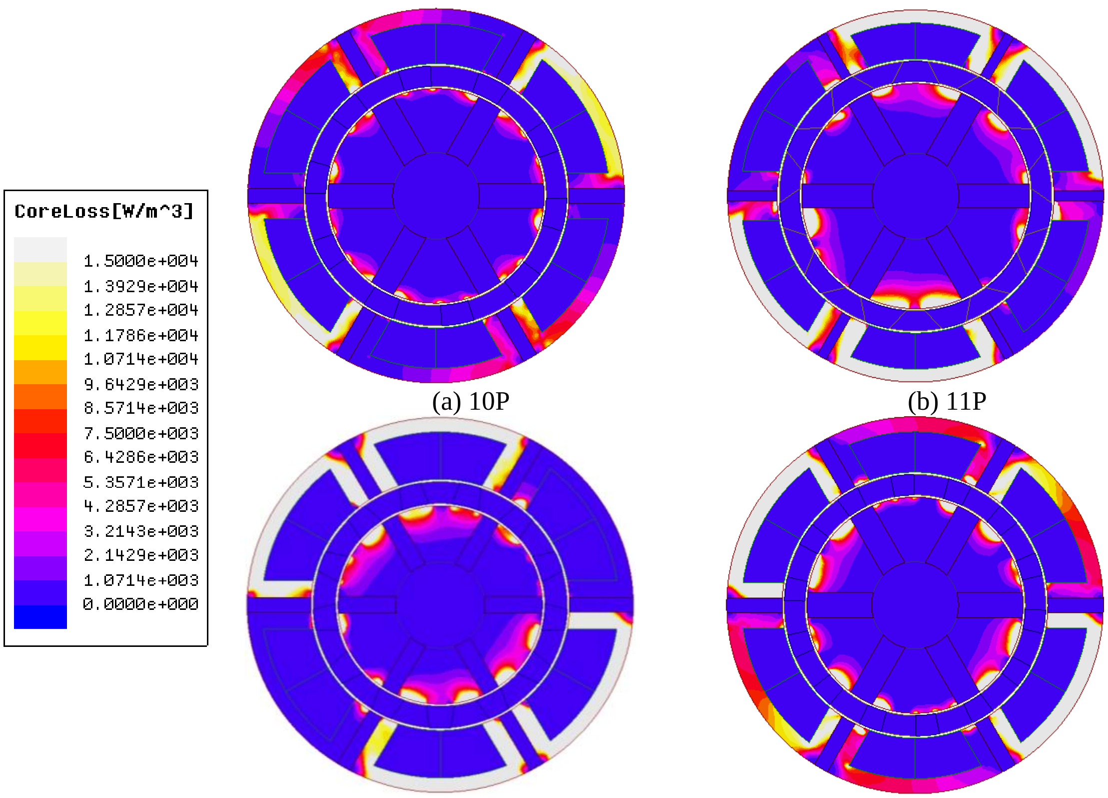
where, I_{rms} is the root-mean-square value of the excitation current, R is the phase resistance of the conductors.

$$R = R_1[1 + \beta(T_2 - T_1)] \qquad (2)$$

where, R_1 is the initial resistance at ambient temperature, R is the final resistance at steady state, β is the temperature coefficient of conductor material, T_1 and T_2 are the initial and final steady state temperatures (Tekgun *et al.*, 2019).

$$\eta = \frac{P_{out}}{P_{out} + W_{magnet} + W_{cu} + W_{fe}} \qquad (3)$$

where, η is the estimated efficiency, P_{out}, W_{magnet}, W_{cu}, and W_{fe} are the output power, eddy current loss due to magnet, copper loss, and total iron loss, respectively.



(a) 10P (b) 11P

(c) 13P (d) 14P

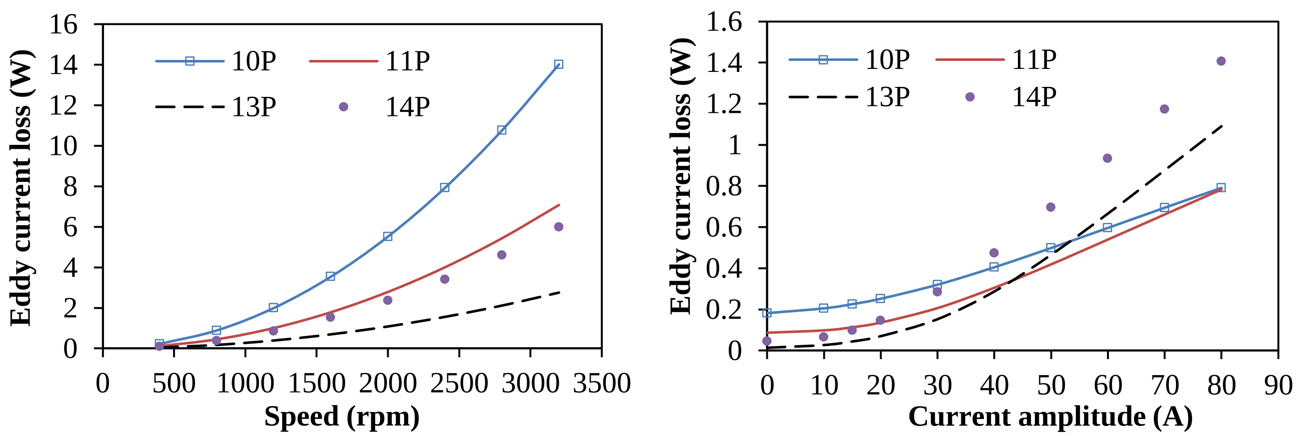
Figure 1: Core loss density maps

3.0 Results and Discussions

Loss accounts of a double stator permanent magnet machine are presented in this section. Figure 2 shows the comparison of magnet eddy current loss of the different machine types simulated over varying rotor speed and current. It is observed that largest amount of eddy current loss is predicted in the 10P machine type, perhaps due to its large pulsating waveforms occasioned by harmonics while the least amount of eddy current loss is recorded in the 13P machine topology. Meanwhile, both the rotor speed and supplied current amplitudes would affect the resulting eddy current loss magnitude in an exponential order. It should be noted that the 10P and 14P machine types have the largest volume of magnet and this would affect the resulting magnet eddy current loss directly.

Table 1: Machine data

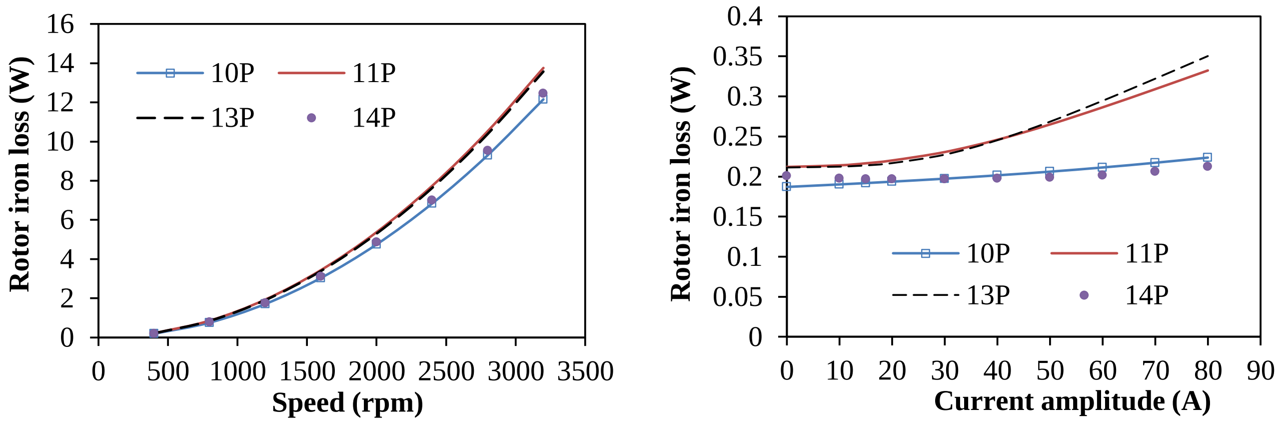
Element	Value			
Inner stator slot teeth	6			
Outer stator slot teeth	6			
Machine active length, mm	25			
Machine diameter, mm	90			
Stacking factor	0.6			
Magnet material type	NdFeB			
Magnet relative permeability	1.05			
Per phase stator resistance, Ω	0.0493			
Object temperature, ºC	22			
Residual flux density, T	1.2			
Number of turns / phase	72			
Estimated copper loss, W	16.64			
Rotor pole number	**10P**	**11P**	**13P**	**14P**
Magnet volume, mm^3	21,064.15	19,005.98	15,745.37	21,064.15
Rotor core material volume, mm^3	8,930.06	11,700.39	9,926.32	8,930.06
Stator core material volume, mm^3	62,997.76	68,016.52	63,947.96	62,997.76
Eddy current loss ripple factor, %	49.87	20.26	16.71	66.37
Electromagnetic power, W, at 400 rpm	441.82	478.15	448.85	273.72
Total loss, W, at 400 rpm	17.39	17.61	17.59	17.44
Efficiency, at 400 rpm	76.70	86.88	86.23	79.92



(a) Magnet eddy current loss versus speed (b) Magnet eddy current loss versus current

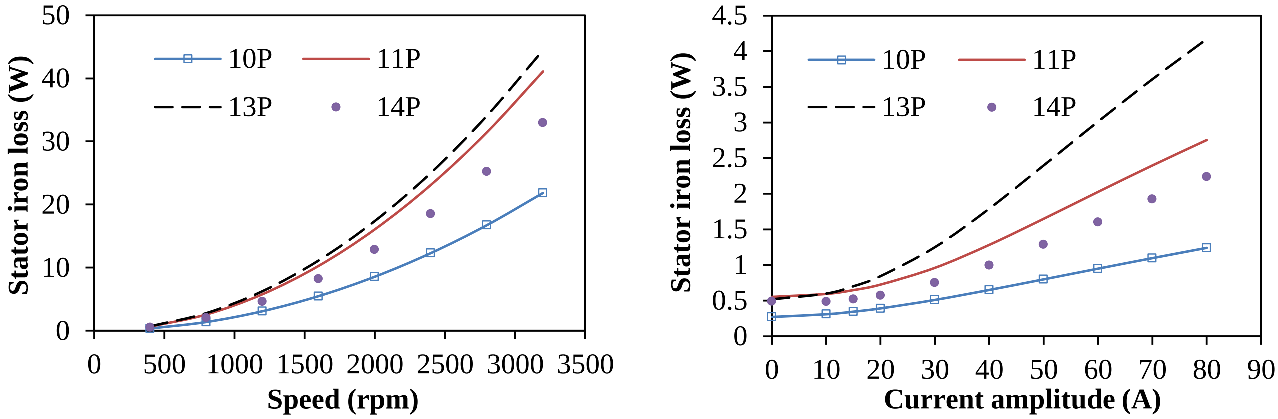
Figure 2: Eddy current loss comparison

Also, variation of iron loss in the rotor section is compared in Figure 3. It is shown that the 11P and 13P machine types have both larger rotor iron loss and stator iron loss magnitudes compared to the machine types with even number of poles, owing to their higher volume capacities. Therefore, it can be concluded that the volume of any given material in an electrical machine, would directly influence the amount of loss in such electrical device; this is supported with the listed volumetric quantities in Table 1. It is also noteworthy that the machine types are optimized separately; thus, the core and magnet sizes have varying values, and hence differing volumes. Note also that rotor losses in each side of the divide i.e. the even and odd rotor pole number machine types, have comparable values within each set. Similarly, the stator iron losses of the compared machine types are depicted in Figure 4. Again, it is observed that the speed, supplied current amplitude and the rotor configuration would have impact on the outcome of the iron loss.



(a) Rotor iron loss versus speed (b) Rotor iron loss versus current

Figure 3: Rotor iron loss comparison



(a) Stator iron loss versus speed (b) Stator iron loss versus current

Figure 4: Stator iron loss comparison

Further, variation of magnet eddy current loss with rotor position of the compared models, at rated speed condition is presented in Figure 5. It is shown that the 10P has the highest amount of eddy current loss; this is followed by the 14P type, likely due to their large loss ripple coefficients/factors usually caused by harmonic effects. The finite element predicted eddy current loss ripple factor in the 10P, 11P, 13P and 14P machine types at 400 rpm and 15 A is: 49.87 %, 20.26 %, 16.71 %, and 66.37 %, respectively. This ripple is usually higher in the machine types that have even number of rotor pole, owing to their inherent high harmonic contents. The influence of harmonics on losses normally originates from the interaction between the stator slots and the magnets, the armature reaction and the non-sinusoidal effect of the supplied current; these harmonics impact on the outcome of magnet eddy current loss could be tremendous, particularly at high speed condition, as stated in Caunes *et al*., (2020). Large chunk of the losses in the system is established to be contributed by the non-sinusoidal nature of the applied currents.

More so, magnet eddy current loss in a system could be reduced through segmentation of the magnets into smaller partitions, the higher the number of partitions the better. The loss quantities in different parts of the machine are provided in Table 1.

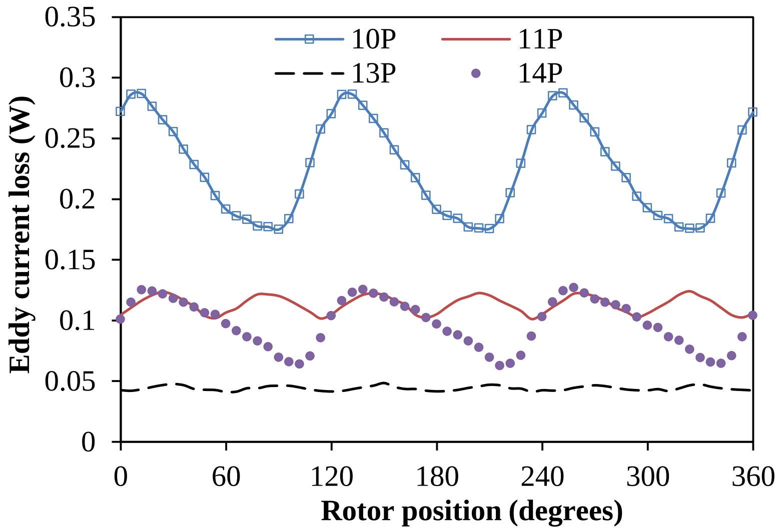


Figure 5: Variation of eddy current loss with rotor angular position

Likewise, the iron loss waveforms in both stator and rotor sections over different rotor positions are depicted in Figures 6 and 7. Although, the rotor iron loss in the compared models are fairly comparable; however, its stator iron loss shows that the size of the material is vital in influencing the overall iron loss content in the machine. Hence, the machine type that has low material volume as seen from Table 1 produces the least amount of iron loss. Meanwhile, the models with even and odd number of poles would have different number of ripple progressions per simulation time i.e. 3 and 6, respectively. This is as a result of the pole combination's impact on the machine performance waveforms. Also, due to the non-uniformity of the airgap circumference, the resulting loss magnitudes would vary in accordance to the airgap flux density values about the rotor positions.

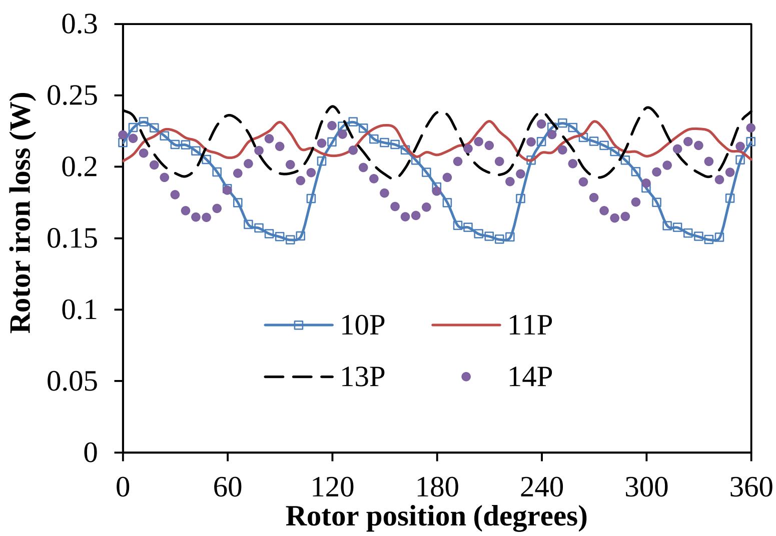


Figure 6: Variation of rotor iron loss with rotor angular position

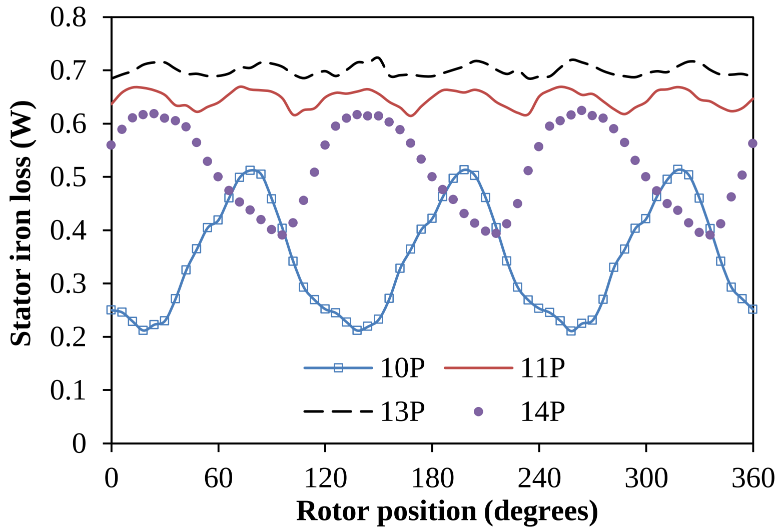


Figure 7: Variation of stator iron loss with rotor angular position

Moreover, the efficiencies of the compared machine types at different electromagnetic output power are displayed in Figure 8. It is obvious that the best machine efficiency is obtained from the 11P machine type; the least performing machine category is the 10P. The efficiencies of the compared machine models could be improved by adopting the model geometric structures which would yield minimal amount of losses through appropriate optimization technique, especially during the design stage; though, most often to the disadvantage of the overall output torque, since the output power and torque variables of any electrical machine are complimentary to each other i.e. an increase in either of the variables would result to a corresponding decrease in the other.

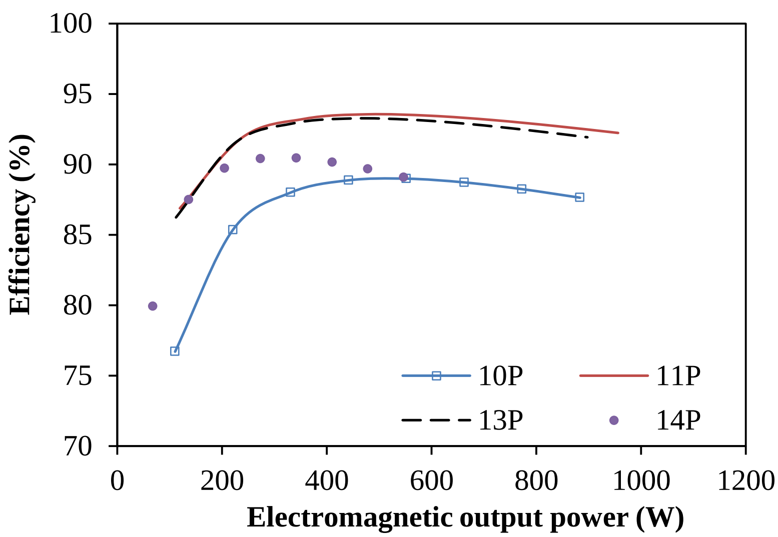


Figure 8: Efficiency comparison at different output power

4.0. Conclusion

The investigation shows that the machine categories having odd number of poles have the most favourable efficiency amongst all due to its admirable electromagnetic output torque and power. It is revealed that the factors which will influence the amount of loss in an electrical machine are but not limited to: its number of poles, supplied current, rotor speed and machine size. More so, it is concluded from the analysis that the resulting loss of a given electrical device is synonymous to its material volume; thus, the larger the volume of the device, the higher its resultant loss magnitude. Moreover, the machine types of similar size which has even number of rotor poles would naturally have larger amount of loss ripple waveforms and/or loss ripple factor compared to the ones with odd number of rotor poles.

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