

Estimation of Losses and Efficiency of Double-stator Switched Flux Permanent Magnet Machines

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ABSTRACT: Losses such as rotor iron and stator iron losses, magnet eddy current loss, as well as efficiency of a double stator permanent magnet machine having varying rotor pole numbers is estimated and presented in this study. This current investigation would be vital for electrical machine designers in quantifying the amount of losses in the various sections of a given double stator electric machine and as well provide better insight on resulting output efficiency of the machine. Time-stepping finite element analysis (TS-FEA) procedure is adopted in the calculations using ANSYS-MAXWELL simulation software. The compared machines having the same stator teeth/pole number (Ps) and different rotor pole (Pr) numbers are designated as: 6Ps/10Pr, 6Ps/11Pr, 6Ps/13Pr and 6Ps/14Pr. The predicted total loss values at rated current and operating base speed is 13.02 Watts, 13.13 Watts, 13.539 Watts, 13.537 Watts, from the 6Ps/10Pr, 6Ps/11Pr, 6Ps/13Pr and 6Ps/14Pr machine types, respectively. The corresponding efficiency of the machine types at rated working conditions is: 81.76%, 88.17%, 86.95% and 78.61%, respectively. The results show that magnitude of losses in a given machine would largely depend upon factors such as number of rotor poles and hence, the machine's operating speed, electric loading and angular rotor position of the machine, etc. It is also found that the number of loss waveform cycles (N_c) in an electric revolution of the investigated machine would depend upon its stator and rotor arrangements. The most performing compared machine types are the ones that have 11- and 13-rotor pole numbers, while the least amount of efficiency is obtained from the machine type that has 14-rotor pole number. Above all, the 6Ps/10Pr and 6Ps/14Pr are characterized with high amount of pulsations or ripples and this is detrimental to the overall performance of the machines.

KEYWORDS: Eddy current loss, Efficiency, Iron losses, Rotor pole, Stator teeth numbers

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I. INTRODUCTION

The general performance of any electric machine is critically affected by its loss components. Although, iron loss prediction has been investigated over a century now, an accurate analytical model is yet to be established owing to the nature of its varying magnetic fields. The effect of these losses on performance of double stator permanent magnet machine is therefore estimated in this work using finite element analysis (FEA) method.

It is shown in Li *et al* (2017) that loss estimation of electrical machines could be quickly realized within a very short simulation time, through analytical technique of using the loss resistance model; however, the accuracy level of finite element analysis is usually overwhelming compared to analytical methods. Meanwhile, loss amplitudes are also noted to be significantly large during field-weakening period of a machine.

Generation of eddy current loss in an electrical device could also lead to poor performance of the device; the generated eddy current loss is attributed mainly to sub-harmonic effect of electric loading, as reported in Chen *et al* (2020). It is also noted that the permeability and conductivity

values of any given material is vital in determining its loss contents; therefore, wise choice on suitable material is essential for better electromagnetic performance of the machine. In particular, machines that have high amount of conductivity would yield large magnet eddy current loss values and vice-versa (Al-Timimy *et al*, 2018). However, magnet segmentation is generally recommended for eddy current loss reduction in permanent magnet electric machines and consequently for higher machine performance.

Cheng *et al* (2019) reported that magnet eddy current loss could be significantly reduced in a given electrical machine by using the right geometric sizes of the machine parts as well as by replacing the rare-earth magnets in such system with ferrite magnets, owing to high conductivity disposition of the former; though, to the detriment of resulting output torque. More so, eddy current loss could severely impact on the machine's performance at high operating speed, due to its high rate of changing magnetic fields at such elevated speed. Nevertheless, the situation could be lessened by the use of Halbach magnetization approach, as shown in Xue *et al* (2019). Besides, it is established in Yu *et al* (2018) that high operating temperature could adversely affect the loss profile of an electric machine, due to its direct link with the magnetic flux

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density-hysteresis correlation, as well as its relation with resistivity quantity of the implemented core material.

Similarly, the number of stator slots plus the rotor pole number of permanent magnet machine influences its core loss components, as proved in Castagnaro *et al* (2019). It is also reported that when the supply current is distorted i.e. with non-sinusoidal excitation waveforms; then, the resulting iron loss amplitude could be tripled compared to a situation when the machine is excited with pure sinusoidal currents. This implies that the presence of harmonics escalate the loss quantity in any electrical machine. Li and Zhu (2019) proved that the polarity and placement positions of permanent magnets (PMs) on the stator of electric machines would affect the resultant amount of losses and consequently, the efficiency in such systems. Thus, adequate care should be taken in arranging the magnet positions in the stator and its successive magnetization polarities.

Basically, the amount of losses such as iron loss and eddy current loss due to magnets of a double stator permanent magnet machine is estimated in this work using finite element analysis (FEA) technique with time-stepping method, for potential evaluation and improvement of the machine's efficiency characteristics for future industrial applications. Meanwhile, the predicted results reveal that the 6Ps/11Pr machine would exhibit the most promising efficiency amongst the compared machine types. The sections of this current study is sub-divided into five. The background of study and the applied materials and methods are presented in Sections I and II, respectively; while the results and its discussion are detailed in Sections III and IV. The conclusion is provided in Section V of the paper.

II. METHODOLOGY

Steinmetz's and Bertotti's orthodox iron loss expression is employed in predicting the iron losses in this present study, as given in Eq. (1). The analyses are carried out with 2D-finite element software. Stator teeth and rotor pole numbers in this work are designated as P_s and P_r , respectively. For instance, 6Ps/10Pr represents 6 stator teeth per stator section and 10 rotor pole number, etc. Note that the inner and outer stator windings are connected in series for higher machine productivity. The applied material constants and other machine elements are listed in Table 1, as given and adopted in (Zhu *et al*, 2005), (Thomas *et al*, 2014) and (Awah and Okoro, 2019). It is worth mentioning that the simulation was done under steady state condition and in two electrical revolutions, in order to avoid the inherent transient errors of the implemented ANSYS-MAXWELL software.

Also, the adopted finite element analysis (FEA) technique is time-stepped. Moreover, the TRANSIENT SOLVER setting of the software is implemented owing to its effectiveness in solving time-dependent magnetic field problems of different electromagnetics sources, simultaneously. However, the presented results are obtained from the second-half of the electric cycle at stable condition, for enhanced prediction accuracy. The core loss density diagrams of the investigated machine types are shown in Figure 1; it is observed that greater portions of both the inner and outer stator core materials portray high susceptibility to saturation.

$$W = k_{hst} B_{max}^\alpha f + k_{exc} (B_{max} f)^\beta + k_{eddy} (B_{max} f)^\alpha \quad (1)$$

where f is the motor frequency, B_{max} is the amplitude of flux density, k_{hst} is the hysteresis coefficient, k_{exc} is the excess loss coefficient, k_{eddy} is the eddy current coefficient, $\alpha=2$, and $\beta=1.5$.

The number of cycles (N_c) of loss waveforms in one electric period of the investigated machine models is same for the even number of rotor poles and the ones with odd rotor pole numbers also have similar N_c amongst its rotor pole number category. It is observed that the analyzed models having odd number of rotor poles have twice this cycle number (N_c) compared to its equivalent yield from the machine models that are supplied with even number of rotor poles. This cycle occurrence is interpreted with a mathematical expression given in Eq. (2). Similarly, the predicted machine efficiency (E_{ff}) is expressed in Eq. (3).

$$N_c = \frac{LCM(P_r, P_s)}{P_r} \quad (2)$$

where, LCM is the least common multiple between the stator teeth/pole (P_s) and rotor pole (P_r) numbers.

$$E_{ff} = \frac{P_o}{P_o + W_{cu} + W_{je} + W_e} \quad (3)$$

where, P_o is the output power, W_{cu} is the copper loss, W_{je} is the iron loss and W_e is the magnet eddy current loss.

III. LOSSES

Loss contents of the investigated machine are examined, under steady state conditions. The presented loss components are the iron losses and magnet eddy current loss; though, the copper loss quantity is incorporated in the efficiency calculation with the help of the winding phase machine's resistance. Figure 2 shows the comparison of magnet eddy current loss having different rotor pole numbers with rotor angular positions and machine speed. It is observed from Figure 2 (a) that the analyzed 6Ps/10Pr machine exhibits high loss pulsation/ripple waveform compared to the other analyzed machine types. This significant loss pulsation would be detrimental to the overall performance of the machine. The predicted loss results of Figures 2 (b), 3(b), and 4(b) show that loss-speed relationship could be represented by non-linear mathematical and exponential expressions.

It is also shown from Figure 2, that the machine types having even number of rotor poles i.e. 6Ps/10Pr and 6Ps/14Pr would have larger eddy current loss than their counterparts that have odd number of rotor poles i.e. 6Ps/11Pr and 6Ps/13Pr. Perhaps, the generated large eddy currents loss amplitudes of the machines could be associated with considerably high amount of harmonics in permanent magnet machines that have even number of rotor poles. These harmonics could potentially escalate the level of losses in such machines. It is proved that harmonics effect intensifies the level of losses in a given system (Alberti *et al*, 2012). Meanwhile, magnet splitting has been proven to be effective in reducing the amount of magnet eddy current loss in an electromagnetic device (Zhang *et al*, 2019); though, magnet segmentation is not investigated in this present study. It is also worth noting that the magnet loss of

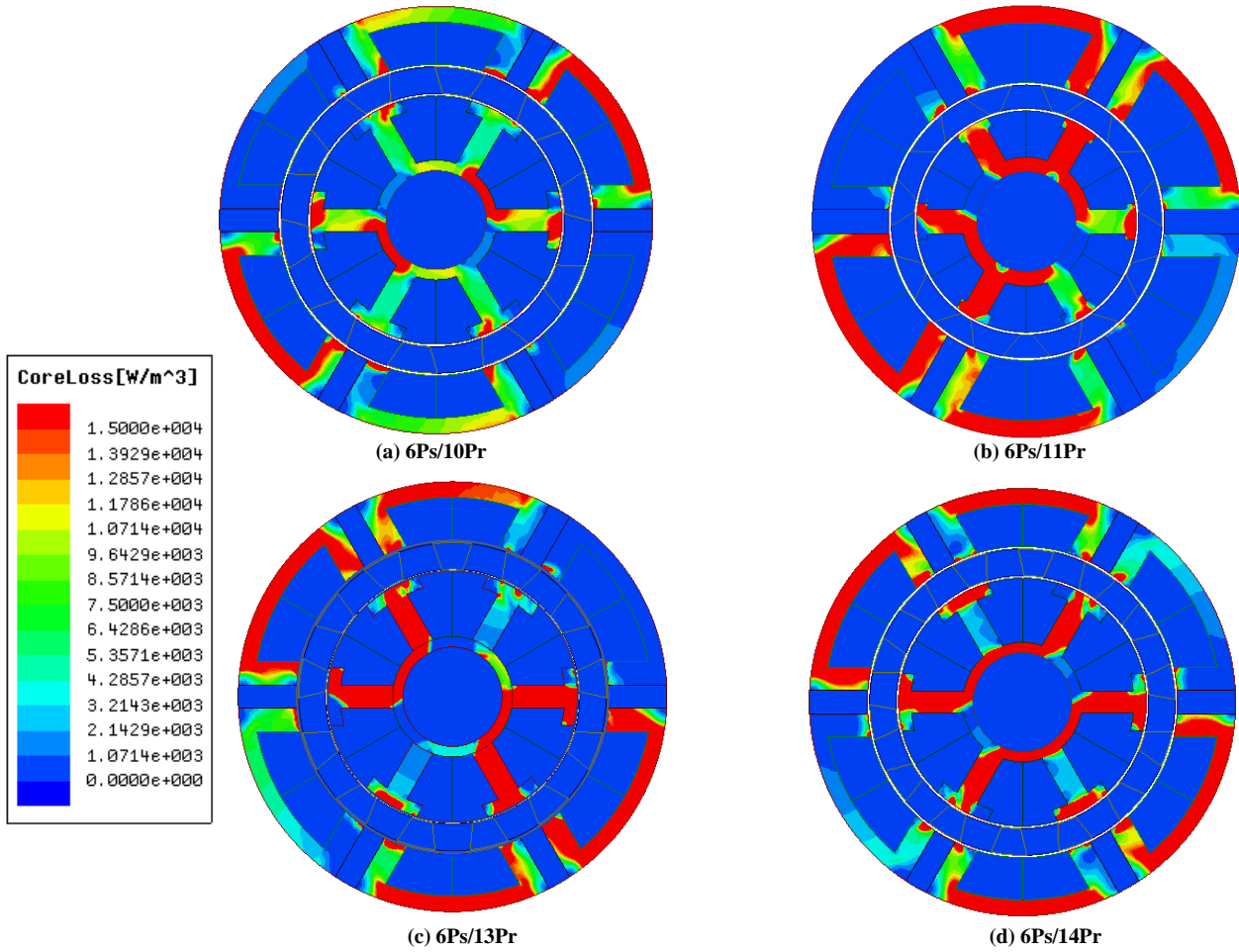
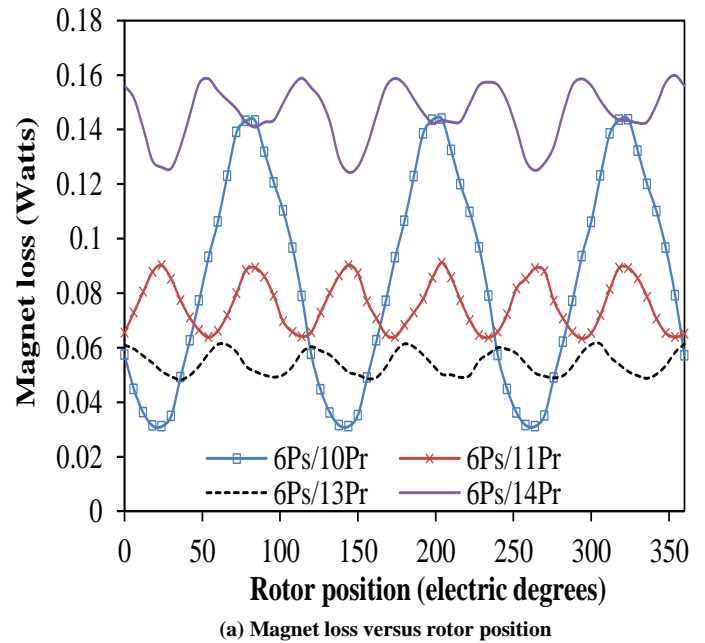


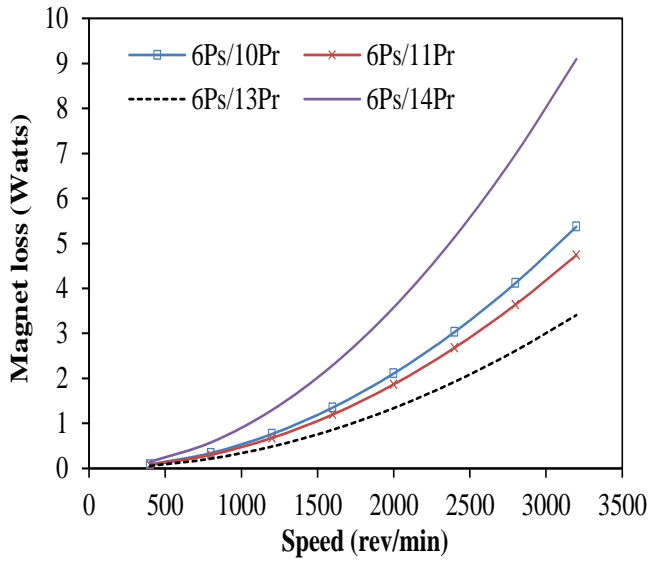
Figure 1: Flux density diagrams.

Table 1: Simulated machine basic data.

Item	Value
Air-gap length (mm)	0.5
Effective machine length (mm)	25
Machine radius (mm)	45
Relative permeability	1.05
Magnet bulk conductivity (Siemens/m)	667000
Magnetic remanence (Tesla)	1.2
Winding packing factor	0.6
Magnet vector magnitude (A/m)	-909456.82
Magnet material	N35SH.
Copper resistivity (Ohm-metre)	1.68e-008
Winding resistance (Ohms)	0.0493
Core material	Electrical steel
Rated current (Amperes)	15
Operating base speed (rev/min)	400
Rated frequency (Hz)	50
k_{hst}	0.0179
k_{eddy}	2.61
k_{exc}	0.0002
Number of turns/phase	72



(a) Magnet loss versus rotor position

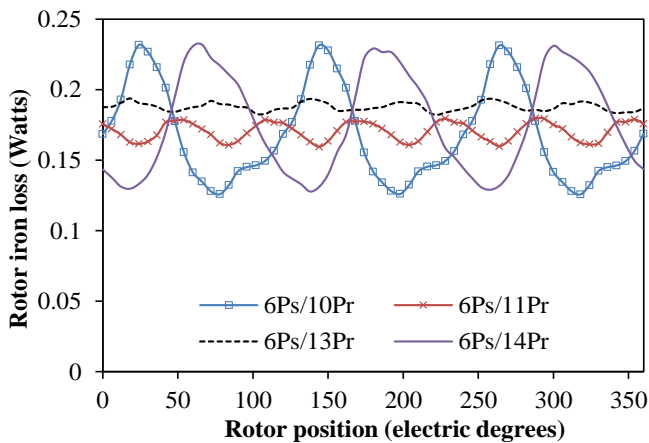


(b) Magnet loss versus machine speed

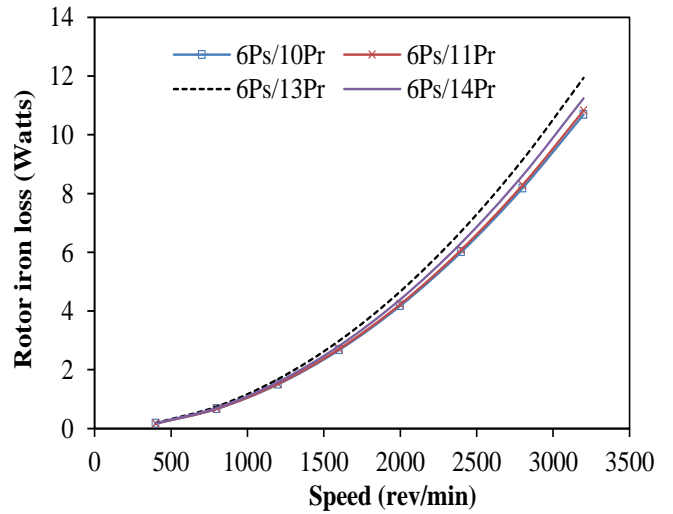
Figure 2: Eddy current loss in the permanent magnet.

any electric machine should be kept at the barest minimal level, in order to avoid consequential demagnetization and possible performance degradation effects, as reported in Zahr *et al* (2014). These undesirable demagnetization and degradation events occur mainly at high operating temperature and high rotational speed.

Similarly, the variations of rotor iron loss with both rotor angular positions and speed are depicted in Figure 3. It is observed that the machine’s rotor iron loss magnitudes are higher in the 6Ps/13Pr and 6Ps/14Pr machine types, since its loss amplitude is dependent on frequency, as inferred from Eq. (1). The rotor core size could also influence the resulting loss magnitude in rotor segment of the machine. The variation of stator iron loss with rotor angular position and motor speed is shown in Figure 4. A similar graphical trend with that of rotor iron loss presented in Figure 3 is observed. The obtained result in Figure 4 is a consequence of both the stator iron size of the machine and its operating frequency, which would indirectly affect the operating speed of the machine. It has been established in literature (Tang *et al*, 2015) that iron loss reduction could be achieved from a given electric machine by skewing its core parts or by deploying improved core materials, as demonstrated in Fang *et al* (2019).

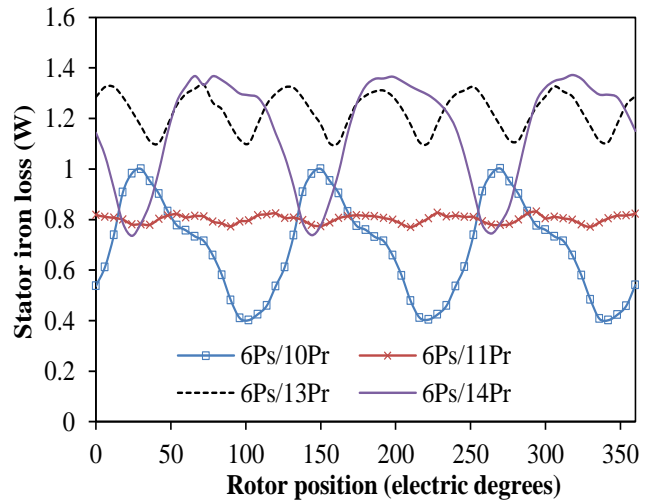


(a) Rotor iron loss versus rotor position

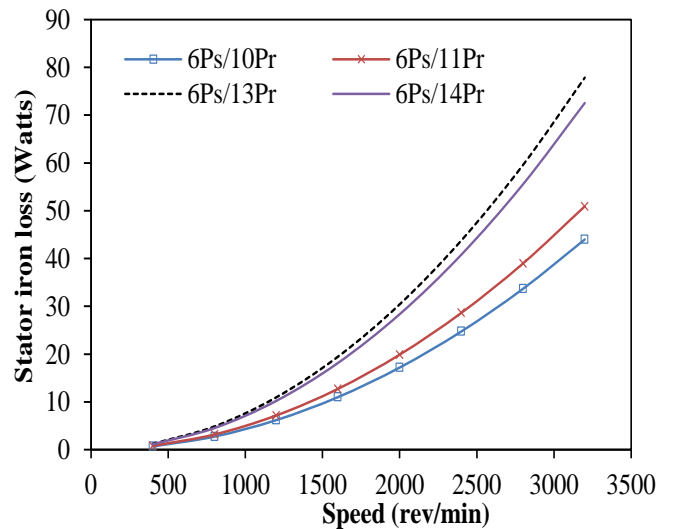


(b) Rotor iron loss versus machine speed

Figure 3: Iron loss in the rotor.



(a) Stator iron loss versus rotor position



(b) Stator iron loss versus machine speed

Figure 4: Iron loss in the stator.

The total losses of the analyzed double stator electric machine include: the sum of rotor and stator iron losses, permanent magnet current eddy loss and copper loss. The losses are also simulated under different electric loading conditions, as shown in Figure 5. The various machine types have fairly similar amount of total loss; however, with very slight differences. The predicted loss values at rated current and base operating speed is 13.02 Watts, 13.12 Watts, 13.54 Watts, 13.54 Watts i.e. from the 6Ps/10Pr, 6Ps/11Pr, 6Ps/13Pr and 6Ps/14Pr machines types, respectively. The implication is that machine types that have higher rotor pole number would have larger loss profiles, likely due to its high working electrical frequency.

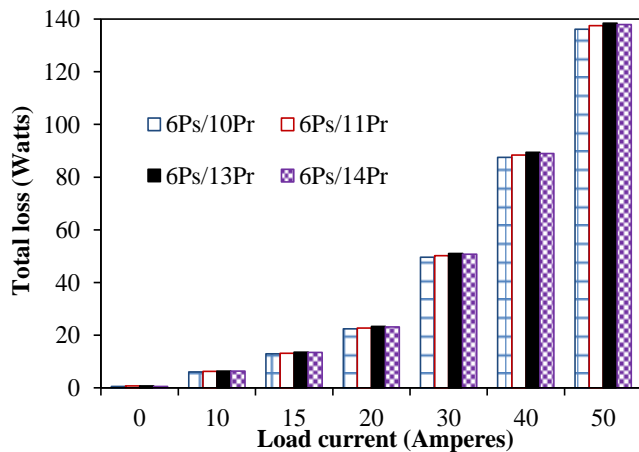


Figure 5: Comparison of total loss.

IV. EFFICIENCY

The efficiency of the investigated machine types is compared and displayed in Figure 6. The results show that the 6Ps/11Pr machine produces the best efficiency amongst the compared machine categories, while the worst case efficiency scenario is obtained from 6Ps/14Pr machine type. Since, the total losses in the machine types are reasonably similar; then, its overall efficiency would be greatly determined by its output power and hence, output torque, as concluded from Eq. (3). The overall efficiency of any electrical machine could be enhanced by implementing adequate loss reduction technique through either appropriate optimization procedure and or the use of suitable soft magnetic materials.

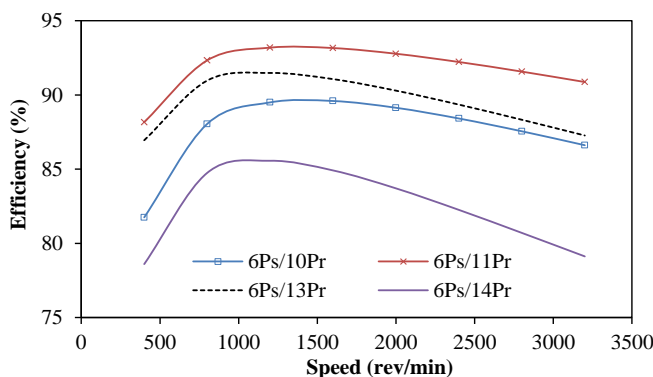


Figure 6: Comparison of machine efficiency.

V. CONCLUSION

The total iron losses and permanent magnet eddy current loss of a double stator permanent magnet machine having different poles are predicted and presented in this investigation. The estimated losses in this work are obtained using finite element analysis (FEA) technique with time-stepping method for potential review and improvement of the efficiency of the machine. The FEA estimated efficiency of the machines at rated working conditions (i.e. at 15A and 400r/min) is: 81.76 %, 88.17 %, 86.95 % and 78.61 %, respectively i.e. from the 6Ps/10Pr, 6Ps/11Pr, 6Ps/13Pr and 6Ps/14Pr machine categories. Hence, the 6Ps/11Pr machine has the best efficiency while the least efficient machine type is the 6Ps/14Pr.

Also, the total loss component of each machine type is reasonably similar, especially at normal and rated operating conditions. However, the various machine types have varying amount of losses in its different segments or sections; particularly, at high operating speed. It is also shown that the stator and rotor pole arrangements, rotor angular speed, load current and rotor angular position would influence the resulting amount of losses in the studied double stator electric machine and by extension to other electrical machines. Moreover, the number of cycles in the loss waveforms is a function of its pole combinations. The presented finite element analysis (FEA) results would provide better loss and efficiency estimation insights of a given double stator permanent magnet machine, for adequate use by electrical machine designers.

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