Effect of Number of Poles on IPMSM Performance

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***Abstract*—Interior permanent magnet synchronous machine (IPMSM) has widely used in the different areas such as electric vehicles. The analysis and design process greatly effect the machine performance. Especially, selection of number of poles greatly effects the machine performance such as machine volume, machine losses etc. This paper deals with analysis of the three different pole number and slot number of IPMSM. Three type of design structure, 6 pole, 8 pole and 10 pole, are compared using FEM. The results of these models are compared and the trade-offs in selecting pole number is discussed. Finally, the most proper number of poles is selected after comparing three different models.**

***Index Terms*—pole number, machine losses, FEM, IPMSM**

I. Introduction

Interior permanent magnet synchronous motor (IPMSM) has performance characteristics such as high efficiency, high power density, high torque density. These characteristics are greatly change by the number of poles. Therefore, the number of pole should be selected carefully in the initial design process to achieve high performance [1]- [3].

In this paper, the comparative analysis of interior permanent magnet synchronous motor (IPMSM) is used to investigate effect of number of poles on the IPMSM performance. Comparison analysis is performed according to various combination of the number of poles and slots using FEM.

This paper process is as follows: The first, three type of designs are analyzed using finite element method (FEM). The second, characteristics of these three type of designs are compared.

In the first part, 6 pole, 8 pole and 10 pole designs are analyzed. These different machines are designed by keeping rotor outer diameter, air-gap length and stator inner diameter constant. The number of slots per pole also kept constant so that 6-pole machine has 36 slots, 8-pole machine has 48 slots and 10-pole machine has 60 slots. All the machines have same total slot area. Therefore, 6-pole machine has larger slot length than others. This allow more turns in one slot. For all designs, total ampere-turns are kept constant. The stator outer diameter is adjusted such that the maximum flux density in stator back iron, stator core connecting teeth, is 2T at maximum current. The volume of magnets is kept constant for all designs. As the pole number increases, magnet width decreases such that all designs have the same torque and induced voltages.

II. Design of Three Types of IPMSM

The design of the three machines are performed referencing to the Toyota Prius 2004 electrical motor. It has 8 poles and 48 slots. The 6 and 10 pole versions of this machines are designed in Ansys Maxwell environments. During the design stage, critical parameters of the original motor such as rated torque, speed and current are kept the same. Three designs have the same stator inner diameter, air gap distance and rotor outer diameter. On the contrary, stator outer diameter and rotor inner diameter change with respect to the pole number by keeping yoke flux density the same for all three designs. The number of slots per pole is kept the same such that 6 pole design has 36 slots and 10 pole design has 60 slots. Three designs can be seen in following figures [4].

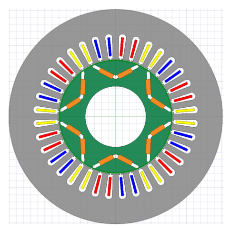

Fig. 1. 6 pole design

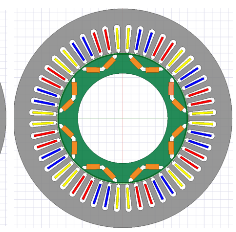

Fig. 2. 8 pole design

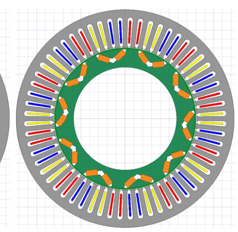

Fig. 3. 10 pole design

As can be seen from above figures, total magnet volume is kept the same by changing magnet length with respect to pole number such that 10 pole design has shorter magnets. By this way, induced voltages of all three designs kept the same for a fair comparison. It is seen that as pole number increases slot area decreases. By this way, total slot area is kept the same with increasing pole number.

Number of turns in a slot is adjusted by keeping current density in slots constant. Thus, 6 pole design has more turns in one slot since 6 pole design has larger slot area.

The parameters of the three different designs are given in Table I.

TABLE I
Motor Design Parameters

	6 pole	**8 pole**	**10 pole**
Slot number	36	48	60
Slot area	x20	x15	x12
Phase current	400A	400A	400A
Number of turns per slot	12	9	7
Electrical period	13.3ms	10ms	8ms
Speed	1500rpm	1500rpm	1500rpm
Torque	400Nm	400Nm	400Nm

The above parameters are calculated in such a way that the current density in a slot and torque are same for all three

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designs. By considering that all designs have the same speed, it is shown that increase in pole number results in increasing electrical frequency.

III. Comparison

In this section, three designs are compared in terms of size, induced voltage, loss and other critical parameters by using FEM.

A. Volume and Size

As the pole number increases, the magnet length decreases in order to keep total magnet volume same for all design. This results in less flux per pole. For all designs, saturation flux density is around 2T for stator back yoke. By keeping maximum flux density at the back yoke close to this value, it is seen that as pole number increases, back core becomes thinner. This situation can be also seen in Figures 1-3. It is shown that 10 pole design has smaller stator outer diameter due to this factor.

The other factor effecting volume is end winding length. The end winding is a portion of a turn that connects torque producing effective parts of the windings. End windings don't contribute to the torque production and they causes copper losses. The end windings of a 6 pole machine can be seen in Figure 4.

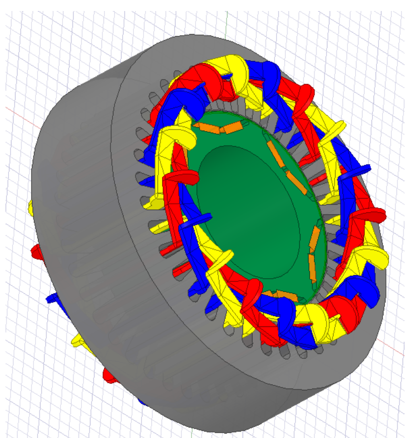

Fig. 4. Example of a figure caption.

As pole number increases, pole belt in mechanical degrees decreases. This results in smaller end winding length for designs with higher number of poles. However, it should be noted that as pole number increases, total number of end windings also increases due to increases number of slots. For different number of poles, one turn with end windings is depicted in Figure 5.

In Figure 5, it is clearly seen that 10 pole design has shorter end winding length. This is better in terms of copper losses. Also, note that axial length of overall machine decreases as pole number increases. This factor effects total volume of the machines. Total volume of the machine is calculated as in 1.

$$V = L * \pi * OD^2/4 \qquad (1)$$

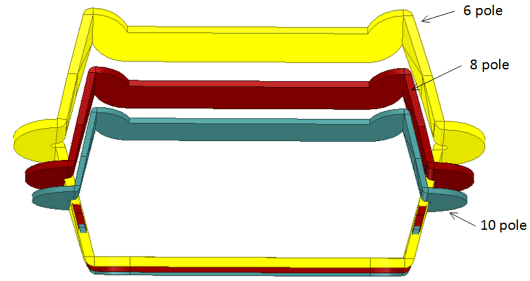

Fig. 5. One 3D turn of 6-8-10 pole design.

where V is the total volume of the motor, L is the axial length of the machine considering axial length of a turn as shown in Figure 5 and OD is the outer diameter of the stator. Using these design parameters, size and volume data for different designs are tabulated in Table II.

TABLE II
Volume Comparison the Machines

	6 pole	8 pole	10 pole
Stator outer diameter	282mm	269mm	262mm
Axial length	165mm	157mm	152mm
Total volume	10.3 lt	8.9 lt	8.2 lt

In Table II, it is shown that volume decreases with increasing number of poles. This is an important outcome of this study. However, increasing pole numbers have some drawbacks, which will be studied in next section.

B. Losses

In a machine, there are mechanical losses, core losses and copper losses. In this paper, last two is analyzed. Firstly, three machines are run at no-load case, i.e. when there is no phase currents, and core losses for machines are acquired using 2D FEM. The core losses under no-load case is shown in Figure 6.

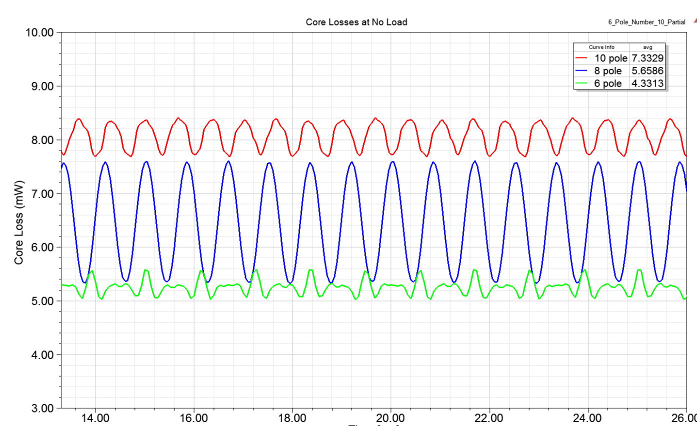

Fig. 6. Core losses under no-load case.

It is shown that under no-load excitation core losses are almost ignorable. As pole number increases, electrical frequency also increases. It is known that core loss is proportional with material volume and square of the electrical frequency. This factor determines core loss in stator and rotor yoke. Since there is no-excitation under this case, there is no copper losses.

Under rated current of 400A operation, core losses increases. Three designs have core and copper losses obtained from 2D FEM as in Figure 7 and Figure 8, respectively.

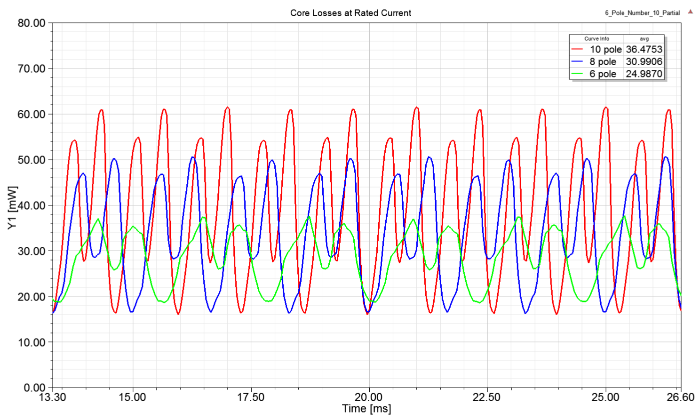

Fig. 7. Core losses under full-load.

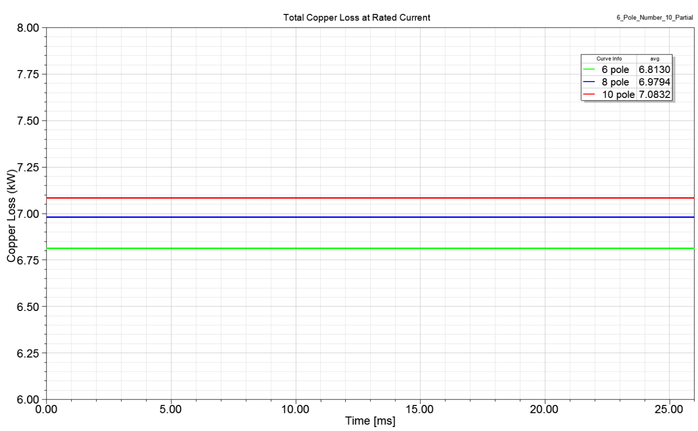

Fig. 8. Copper losses under full-load.

It is shown that 10 pole design has highest core and copper losses. This is another important outcome of this study. Increasing pole number also increases both copper and core losses. Thus, there is a trade of between volume and loss.

C. Induced Voltages

Induced voltages for three designs are compared under no-load excitation at 1500 rpm. In this case, there is no current in phases and voltage measured at the terminals are equal to the back emf, which results from flux linked by phases created by permanent magnets. Line to line induced voltages can be seen in Figure 9.

As can be seen in Figure 9, all designs have the same peak to peak magnitude of induced voltages. This is expected since total ampere-turns for all designs are the same and same magnet volume is used for all. Flux linkages are also the same.

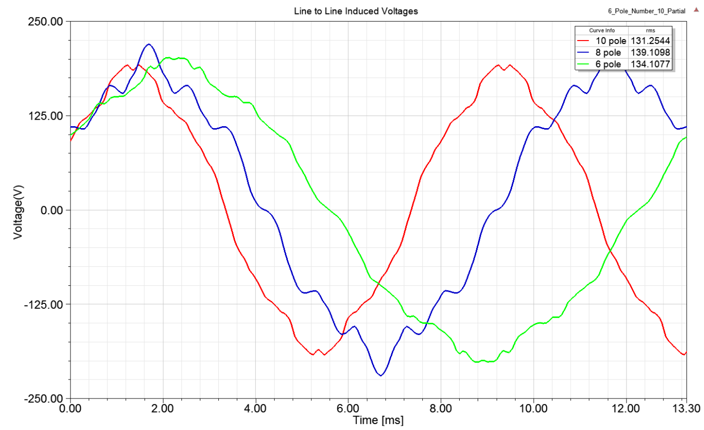

Fig. 9. Induced voltages under no-load.

It is stated that for lower number of poles, slot area is large and high number of turns are used althoug total number of turns are the same for all designs. Another point to note in Figure 9 is that designs have different periods. It is stated that as pole number increases,for the same speed, electrical frequency increases.

D. Other Parameters

In this subsection, some other critical parameters are compared for different machines. Torque produced under same excitation and torque ripple are compared for all machines. For the comparison, all machines are run at 400 A of maximum phase current and load angle of 45 deg. The results are shown in Figure 10.

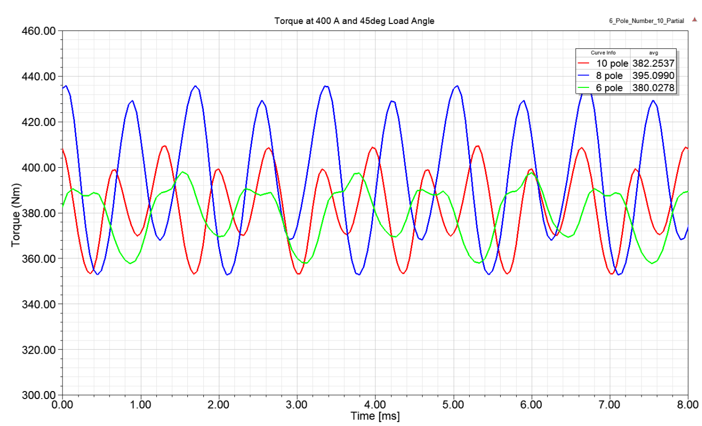

Fig. 10. Torque under rated current.

It is known that pole and slot number selection has significance effect on torque ripple. In the analysis, it is shown that maximum torque ripple is observed for 8 pole design. All designs have almost the same average torque.

In this study, magnet flux linkage, direct and quadrature axis inductances of all designs are also compared. These parameters are calculated using finite element analysis on Maxwell. Magnetic flux linkage is peak flux linkage of any phase under no-load excitation. Quadrature and direct axis inductances are calculated from inductance matrix obtained from Maxwell and using transformations. These values tabulated in Table III.

TABLE III
MAGNET FLUX LINKAGE AND INDUCTANCES

	6 pole	**8 pole**	**10 pole**
Ψ_{PM}	237 mWb	168 mWb	125 mWb
L_d	0.79 mH	0.54 mH	0.45 mH
L_q	2.3 mH	1.6 mH	1.3 mH

It is observed that inductances are higher for small number of poles. This is expected since there are higher number of turns per slot in designs with small number of poles. It is known that inductance is proportional with square of number of turns.

$$\frac{V_{DC}}{\omega\sqrt{3}} = \sqrt{(-L_q i_q)^2 + (L_d i_d + \Psi_{PM})^2} \tag{2}$$

where V_{DC} is dc link voltage and ω is base speed in electrical radians per second. Using the electrical parameters calculated in Table III, base speed of the machines are calculated as in Table IV.

TABLE IV
BASE SPEEDS IN MECHANICAL RAD/S

	6 pole	**8 pole**	**10 pole**
ω_{base}	150 rad/s	160 rad/s	166 rad/s

Electrical frequency increases with increasing pole numbers. Electrical frequencies for all design is tabulated in Table V. Switching frequency is suggested to be around 20 times of electrical frequency, as a rule of thumb. Suggested switching frequency for each design is also tabulated in Table V.

TABLE V
ELECTRICAL AND PROPOSED SWITCHING FREQUENCIES

	6 pole	**8 pole**	**10 pole**
Electrical frequency	75 Hz	100 Hz	125 Hz
Switching frequency	6 kHz	8 kHz	10 kHz

IV. CONCLUSION

This paper deals with three types of IPMSM as the pole number of 6, 8 and 10. 10-pole machine has lower torque ripple than 6-pole and 8-pole machines. Since, all three designs have same flux linkages, they all have almost same torque value and almost same induced voltages. The stator outer diameter and end winding length decrease as the number of pole increases. Therefore, the volume of machine decreases as the number of pole increases. So, the higher pole number means that higher torque density, higher power density. But, the core losses increase as the pole number increases. 10-pole machine has an electrical frequency 1,67 time of 6-pole machine's electrical frequency. On the other hand, 6-pole machine's volume is equal to 1,26 times of 10-pole machine's volume. Core loss proportional to square of frequency and proportional to volume. Thus, core losses increase as the number of pole increase. The copper loss also increases as the number of pole increases. This reduces the machine efficiency. In conclusion, one should consider the trade-off when selecting the number of poles of IPMSM. It should be considered by design requirements. From the results obtained in this paper, the most proper pole number is seemed to be 8. Because, it's volume is not much greater than 10-pole but it's core losses are much smaller than 10-pole.

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